THE ROLE OF PIEZOCERAMIC MICROACTUATION FOR FUTURE JPL MISSIONS

Sarita Thakoor, John Michael Morookian, and Jim Cutts

The overall objective of the proposed effort is to develop a *flexible* microactuator based on tailored films of lead lanthanum zirconate titanate, PLZT (deposited on flexible substrates) and to demonstrate a multifold enhancement in its force/displacement capabilities, compared to those of the current state-of-the-art actuators based on bulk ceramic materials. The effort will be especially aimed at realization and demonstration of the promise of high efficiency actuation of an optimized thin film based bimorph structure by *contact-less optical activation* in addition to the conventional electrical actuation mechanisms.

Flexible microactuators are envisioned by depositing tailored thick (~ 2-10 micron) films of active materials on judiciously chosen, strong flexible (polymeric) substrates. Such flexible microactuators would enable a new generation of non-silicon based microelectro- mechanical and micro-opto-mechanical systems where the actuation will not be restricted by the clamping effect due to the rigid substrate as in the current silicon based micromachined structures. Also in the current micromachined structures, the actuation force out of the structure is limited by the thickness to which the micromachined structures could be grown. Deposition of tailored piezoceramic thin films on flexible substrates would substantially eliminate the substrate clamping effect and thicker films can be deposited by high rate deposition processes, leading to mobile elements with substantially higher force to input power ratio. The key technical challenge is to obtain a tailored PLZT film well adhered to a suitable flexible substrate. 'This will be addressed by a three pronged approach: (a) development of a process to deposit piezoceramic thin films on high temperature polymeric substrates (such as polybenzo-oxazole) (b) lowering of crystallization temperature of PLZT and (c) delaminating films from high temperature substrates for their subsequent 'lamination' onto flexible substrates such as mylar/kapton. Furthermore, optimization of the material with respect to its defect density, absorption coefficient, optical quality, spontaneous polarization direction, and bimorph geometry could lead to a substantial (up to two orders of magnitude) enhancement in the photoactuation efficiency and thereby allow exploitation of the full potential of the optical actuation effect for photonic control of mechanical motion. Such a flexible, optically triggered microactuator would eliminate the need for an on-board electrical energy source, and open up numerous possibilities of small, light-weight, deployable, optically triggered, contactless actuators, and even solar power driven advanced mobility. Proof-of-concept demonstration of flexible actuators in year 1 and demonstration of the potential of the selected DARPA application in year 2 is the focus of this proposal.

Flexible microactuators constitute an enabling technology for insect -explorers (a new class of small vehicles with advanced mobility emulating, the small and agile characteristics of insect mobility combined with dedicated sensing ability) In turn, due to their promise for exploration of difficult, hard to reach terl-sin, insect explorers will be ideal for a variety of applications including law enforcement, inspection of hazardous environment, search and rescue in disaster areas such as earthquake sites etc. Additionally such flexible microactuators will be useful for high precision surgery, optical micropositioning, solar tracking actuator/shutter, direct corrective control in adaptive optics/interferometry, and photophones.

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1. *INTRODUCTION:*

1.1 Need for flexible microactuation:

The emerging field of micro-electro-mechanical systems (MEMS) and micro-opto-mechanical systems (MOMS) holds a promise of revolutionary developments for DoD applications ranging from autonomous mobility platforms (micro- Unmanned Aerial Vehicles), medical diagnostic tools to petaflop computing, On the other hand, NASA's vision of future microspacecraft entails reduction in size of all spacecraft components by orders of magnitude. A breakthrough in actuation technology is required to obtain such size reduction for the next generation DOD and NASA micromobility applications, in the commercial application area, there is an urgent need to miniaturize the size of end-effecters on the medical diagnostic tools such as micro-catheters or endoscopic manipulators, to enable minimally invasive surgery without compromising the mobility and flexibility.

1.2 Advanced Mobility:

In-situ, autonomous exploration and intelligence gathering from surfaces, subsurfaces, and environments for a variety of application scenarios will benefit from a totally new class of exploring vehicles: small in size, mobile and agile like insects, equipped with dedicated micro sensors, Large numbers of such inexpensive, and therefore dispensable, explorers would supplement the functions performed by traditional exploration modes. Furthermore, their dedicated sensing functions and small size would be invaluable in hazardous or difficult-to-reach territories for scouting missions. One approach for realization of such vehicles is evolutionary: through the miniaturization of existing wheeled vehicles. Another approach which might offer significant advantages, especially when traversing unusual and difficult terrain such as loose granular surfaces, is to imitate the mobility attributes of insects. Mimicking biology, such artificial insects may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration. They would combine the functions of advanced mobility and sensing with a choice of electronic and/or photonic control, Preprogrammed for a specific function, they could serve as "no-uplink, one-way communicant ing" beacons, spread over t he explorat ion site, *looking for the object of interest.*

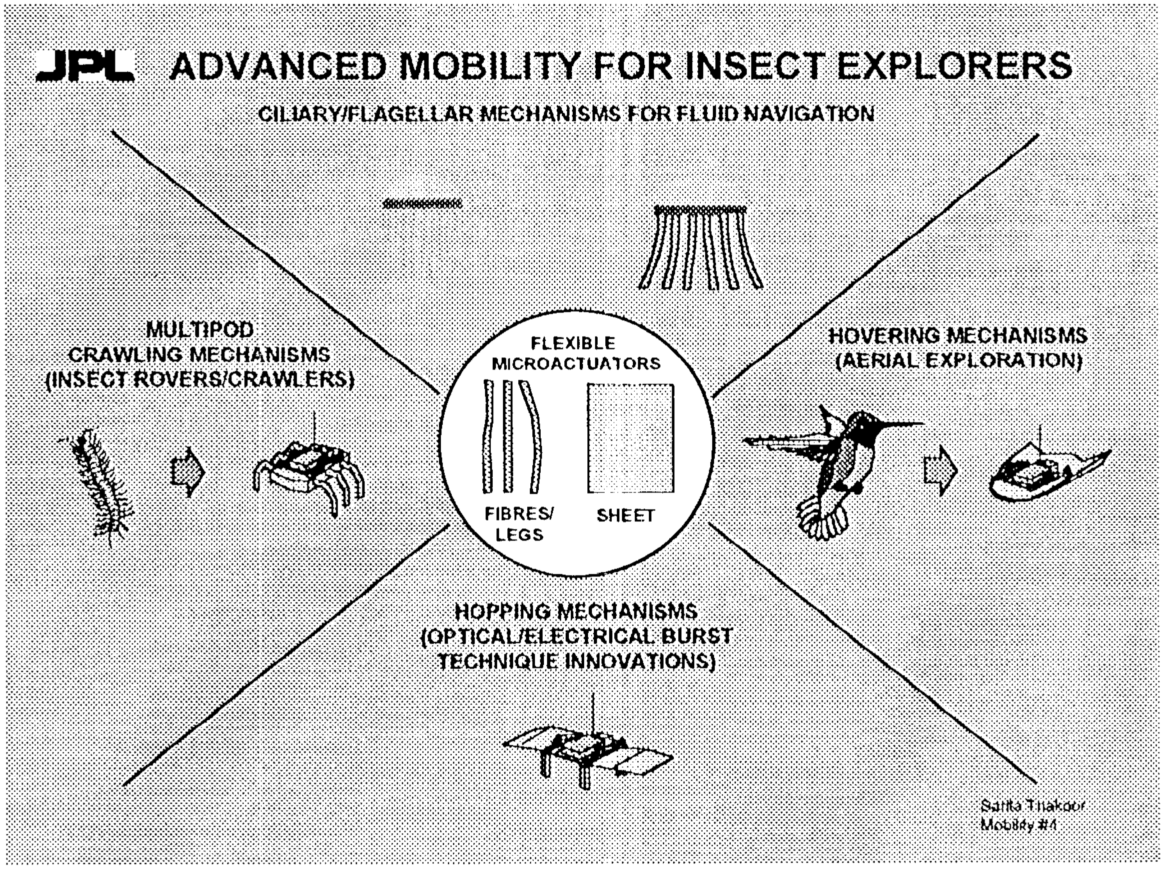


Figure 1

A breakthrough in actuation technology is required to realize the variety of advanced mobility mechanisms for such "insect explorers". ***Flexible microactuators must provide a high strain and force combination with low power consumption, and must work over wide temperature ranges.*** Figure 1 illustrates four different kinds of insect explorers/in-situ explorers[1] emulating biological mechanisms:

A. Multipod crawl ers for surface explorations maneuvering through soft soil and difficult terrain, adaptive to the environment,

B. Ciliary / Flagellar Explorers for navigation through fluids (for e.g. underwater exploration for Naval applications)

C. Hopping Mechanisms for surface and aerial exploration

D. Hovering Explorers for aerial proration

Flexible microactuators that could be addressed/controlled optically and/or electrically would be an enabling technology for insect -explorers. in turn, due to their promise for exploration of difficult, hard to reach terrain, insect explorers will be ideal for a variety of applications including law enforcement, inspection of hazardous environment, search and rescue in disaster areas such as earthquake sites. Additionally such flexible manipulation could also be used for high precision surgery, optical micropositioning, solar tracking actuator/shutter, direct corrective control in adaptive optics/interferometry, and photophones.

2. *BACKGROUND - EXISTING ART*

Polymeric actuators[2] based on polyvinylidene difluoride (PVDF) and polymethyl-methacrylate (PMMA), although proven for tactile sensing and some high strain applications, have been used with limited success for mobility applications due to their limited force capacity and restricted temperature range of operation and therefore limited cyclability. Some recent[3,4] work on isodactic PMMA has reported high displacements, although the exact nature of the observed effect (coulombic or electrostrictive) and its cyclability with temperature, are matters of continuing research. Therefore, its potential for providing high strain/force combination and useful work over a wide temperature range is unclear, ionic conducting polymer gel films (ICPF) discovered by Oguro et al[5] in 1992 have received substantial attention to-date[6,7]. However, the response speed of these actuators is rather slow (several seconds), the drive current is high, temperature range of operation is limited, and they work only in aqueous medium. There is a need for flexible microactuators that could provide a high strain and force combination for low power consumption, and could operate over a wide temperature range for the variety of advanced mobility applications identified above.

.?. *PIEZOCERAMIC FLEXIBLE MICROACTUATORS:*

3.1 **Why piezoceramic films/microact uators:**

~'able 1 presents a comparison of the different actuation technologies and illustrates why piezoceramics are the leading candidate, especially when dimensions shrink and approach those of thin films, where properties are generally tailorable by fine composition control Thin film growth techniques through their close control on composition allow a much finer control of hysteresis and aging properties.]n particular, the lower holding power requirement by piezoceramics makes them attractive over magnetic actuators which suffer from the need for significant heat dissipation. With size reduction, the energy absorbed by piezoceramics could be up to over two orders of magnitude higher[8] compared to electrostatic and magnetic actuators (Figure 2). This higher density is attributed to the higher dielectric constant and the dependence of the breakdown field as a function of thickness[8]. Furthermore, piezoceramics offer the potential of solar driven, tetherless mechanisms since they can be actuated[9-11] directly by optical illumination (350nm to 450 rim). Piezoceramic actuation is potentially robust, amenable to low temperature (deep space) operation, and intrinsically radiation-resistant. in addition, their ability to be batch-produced by thin film manufacturing techniques on large substrate areas offers convenience and cost effect iveness.

WHY PIEZOCERAMIC ACTUATION?

(AS WE SCALE DOWN TO THIN FILM PIEZOCERAMICS)

			POLYMERIC MATERIALS		
	PIEZOCERAMIC	SHAPE MEMORY ALLOY	PVDF	Polymides PMMA Polyurethanes	MAGNETO-STRICTIVE
MECHANISM	PIEZOELECTRIC & ELECTROSTRICTIVE	THERMAL: MARTENSITIC -> AUSTENITIC PHASE CHANGE	PIEZOELECTRIC, PHASE TRANSITIO	ELECTRO-STRICTIVE	MAGNETIC FIELD IN DUCED BY COIL
STRAIN	10^{-4} TO 10^{-1}*	10^{-3} TO 10^{-1}	10^{-4} TO 10^{-1}	10^{-4} TO 10^{-2}	10^{-6} TO 10^{-2}
TORQUE	HIGH ~100 kgm FORCE	LOW-MEDIUM ~1 kgm FORCE	SMALL	SMALL	HIGH
HYSTERISIS	TAILORABLE BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	LARGE
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	-196°C -> 300°C WIDE	-196°C -> 100°C WIDE	-10°C -> 60-C LIMITED	-10°C -> 80°C LIMITED	-273°C -> 100°C WIDE
RESPONSE SPEED	μsec-msec	seconds	meet	msec	μsec-msec
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	LOW	LOW	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	YES	TBD	TBD	TBD	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR-POOR	GOOD
PROSPECT OF MINIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAJ R

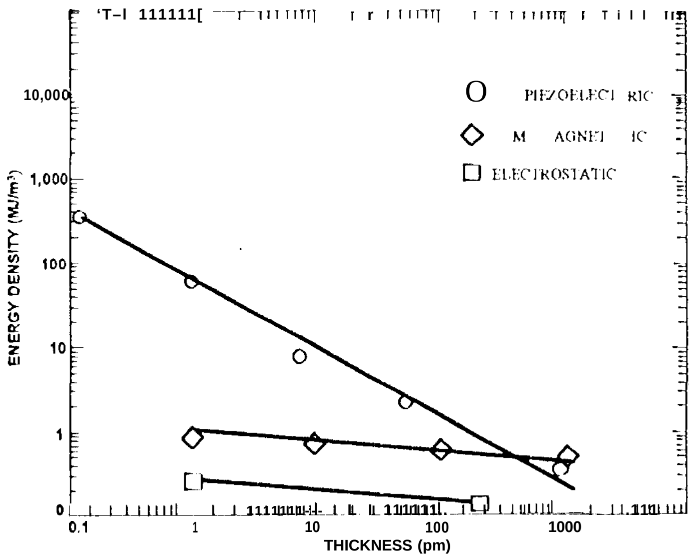
PIEZOELECTRICS REPRESENT A LEADING CANDIDATE FOR ADVANCED MICROACTUATION

" Wdh amplification techniques (e. g. optically or ● lectrically activated bimorph, flextensional elements and combination thereof to obtain double amplification)

Table 1

3.2 Electrically Activated Actuation:

The electrically activated piezoceramic actuation based cm tailored bulk materials is well established and used in several applications. } Iowever, the high voltage (>100 V) required for piezoceramics is undesirable as the actuators would scale down in size. Flexible microactuators on the other hand based on tailored thin films (~ 2 micron thick) deposited on selected flexible substrates promise substantially higher (~ **20** times) energy density (figure **2)** compared to a 200 micron thick ceramic wafer, could be operated at 5 V to provide enhanced force per unit input power. Moreover, due to the lower power consumption (extremely low holding current), the ratio of generated force to input power for a 2 micron thick film microactuator could be ~ 4 times higher to that in the state of the art ceramic.

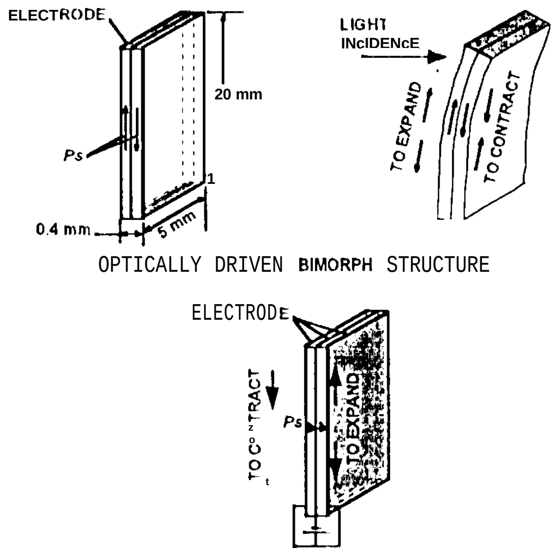


Energy density as a function of film thickness
Figure 2

3.3 Optically **Activated Actuation:**

Two oppositely poled lead lanthanum zirconate titanate (PLZT), ceramic wafers bonded together to form a piezoceramic bimorph (as shown in fig 3a) exhibit a large photodeflection, analogous to a piezoelectric bimorph. A deflection as high as -200 micron, away from the direction of the light, has been obtained from a bimorph ~2 cm long, 0.5 cm wide, and -0.4 mm thick, when exposed to an intensity of- 80mW/cm^2. in such a deflection, a force of -10 gm is generated at the tip of the bimorph. in fact, PLZT ceramic wafers have been earlier used[13,14] to demonstrate two different kinds of mobile walking and gripping devices based on such photoactuation in ceramics, However the limited photonic energy to mechanical conversion efficiency (- 0.1 %) obtained in the ceramic due to its poor optical quality left those demonstrations as mere curious experiments. ***With** the **recent emergence of thin film growth techniques for piezoceramic PLZT films, a new opportunity has arisen in exploiting the full potential of this optical actuation effect for photonic control of mechanical motion***. As detailed in the next section, optimization of the material with respect to its defect density, absorption coefficient, spontaneous polarization direction, and bimorph geometry (aspect ratio, etc.) could lead to a substantial (up to two orders of magnitude) enhancement in the photoactuation efficiency. A flexible PLZT film microactuator thus enhanced, clearly would bypass the need for an electrical energy source, and open up numerous possibilities of deployable, optically triggered, contactless actuators, and even solar power driven advanced mobility.

Clearly, such *advanced mobility (ciliary/flagellar mechanisms, multipod inchworm/crawling mechanisms)* would be tetherless, and either autonomous or remote-controlled. The prohibitive weight and mobility restrictions due to an umbilical power cord would be eliminated. The photogenerated deflection could be used to directly "walk" on the surface or to run motors for indirect locomotion. Such tetherless optical control of advanced mobile vehicles would also be desirable for exploration of hazardous, hard to reach locations, as long as at least a line of sight exists. Piezoceramic bimorphs provide a good trade of load versus displacement for piezoceramics and have been used for a variety of applications. optically driven bimorphs have a similar niche for applications requiring high displacement and low load requirement with the added versatility of photonic addressing.



OPTICALLY DRIVEN BIMORPH STRUCTURE

VOLTAGE DRIVEN BIMORPH (OPTICAL EFFECT IS SMALL OR NOT MEASURABLE)

Figure 3

Figure 3 compares a optically driven bimorph with a traditional piezoelectric voltage driven bimorph[15]. The optically driven bimorph is poled in the plane of the substrate as shown in figure 3a. On the other hand, the poling in a voltage driven bimorph is perpendicular to the plane of the substrate as shown in figure 3b.

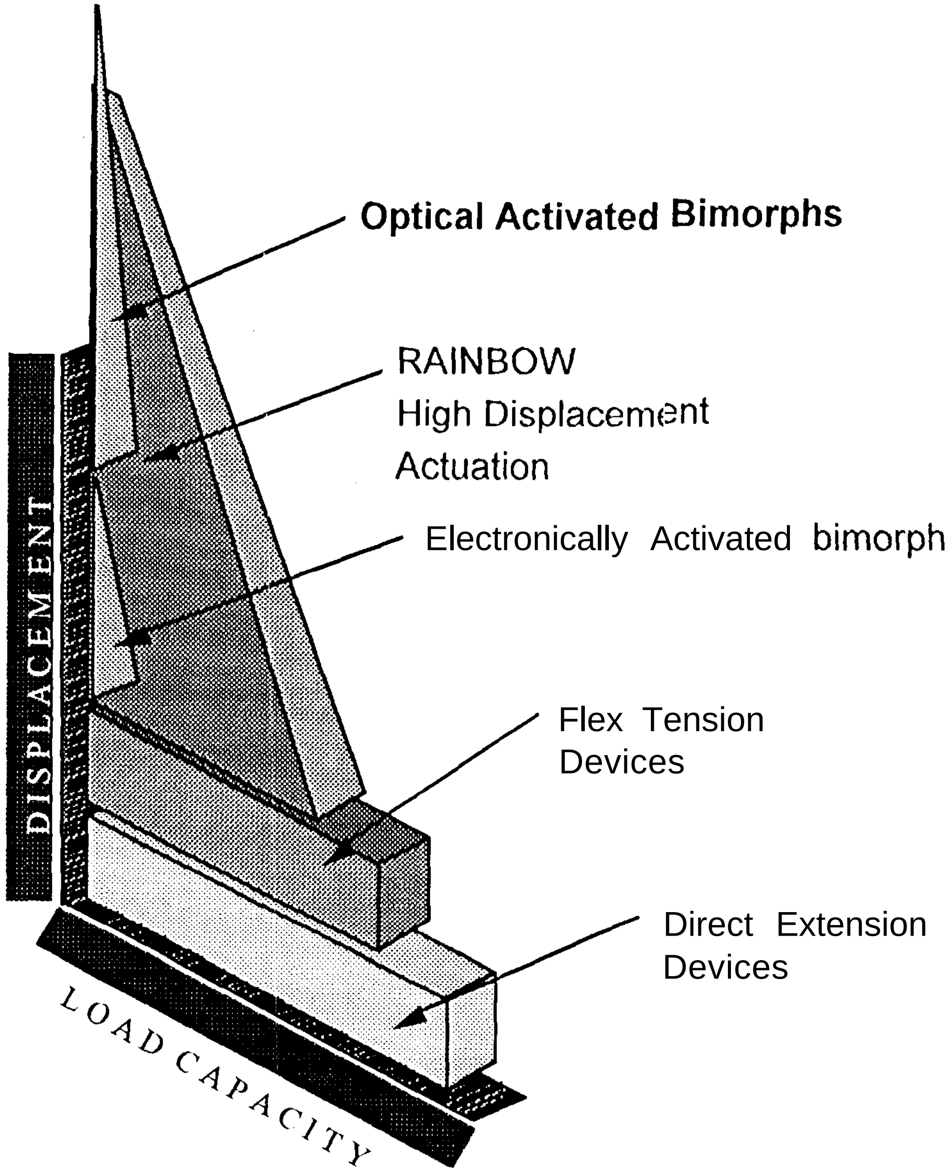


Figure 4

Figure 4 further shows the track of load versus displacement for piezoceramics and their different amplification modes such as electrically/optically driven bimorphs, RA1N11OWS and flex-tensional amplification techniques. Optically driven bimorphs have a niche for applications requiring high displacement and low load requirement.

4. SIGNIFICANCE AND INNOVATION:

Flexible microactuators are envisioned by (depositing tailored thick (~ **2-10** micron) films of active materials on judiciously chosen, strong flexible (polymeric) substrates. **Flexible microactuators would provide a high ratio of generated force to input power for**

comparable surface areas, required for a variety of advanced mobility applications, potential advantages of flexible microactuators are:

- low power (low voltage operation, < 5 V), low mass, low volume
- high force/volume, high force/power
- higher deflection
- flexible, miniaturizable microactuator: scaleable for MEMS/MOMS
  excellant cyclability -more than million cycles
  amenable to both electrical or optical activation

Schematically fig 8b (on page 16) illustrates such a flexible actuator, It can be formed in the form of fibres or sheets (figure 1) as demanded by the application.

The significance of the proposed work is two fold. First, the high energy density offered by piezoceramic thin films, allows up to four times enhanced ratio of output force to input power from a single film bimorph. Second, is the promise of up to two orders of magnitude enhanced deflection efficiency in a piezoceramic flexible bimorph when activated optically accompanied with about two times higher ratio of output force to input power. Specifically optical control has following advantages:

- contactless control/remote control
- low power solution
- electrode-less, contact less structure
- enhanced reliability , external voltage not required (breakdown issues avoided)
- microdisplacement proportional and cent roll able by the int ensit y of the light energy

Such flexible microactuators would enable a new generation of non-silicon based microelectro- mechanical and micro-opto-mechanical systems where the actuation will not be restricted by the clamping effect due to the rigid substrate as in the current silicon based micromachined structures. Also in the current micromachined structures, the actuation force out of the structure is limited by the thickness to which the micromachined structures could be grown. Deposition of tailored piezoceramic thin films on flexible substrates would substantially eliminate. the substrate clamping effect and thicker films can be deposited by high rate deposition processes, leading to mobile elements with substantially higher force to input power ratio.

.$'. *APPROACH:*

'l'he technical approach to develop and demonstrate flexible microactuators therefore will aim at the overall optimization/maximization of the extent of deflection combined with a low power, high force capability using electrode less optical activation, This will be done within the following five distinct workitems that sequentially depend on each other:

5.1 Optimization of Photoactuation in Ceramic Bimorph Structures: This subtask will combine Penn State's unique capability to tailor-make ceramics with optimum doping for the photoactuation effect and JPL's unique-expcr-tisc in high speed photoresponse investigations, thin film device design and applications, It is known that the optical actuation effect (extent of the photodeflection) is a direct but complex function of (1) material microstructure, crystalline orientation, and the actual geometry (configuration/ structure/ dimensions, etc) of the bimorph; and (2) the intensity, and angle of incidence of the light illumination, triggering the effect, This subtask will consist oftbe following sub-work items:

a. Optimization of the Effect: Establish a quantitative interdependence (and cross correlations) among the piezo properties, photodeflection, and material characteristics (micro-structure, crystal orientation, etc) by systematically studying the behavior of the materials with respect to:

thickness of the ceramic wafer to verify the "penetration depth" hypothesis,
composition variation and selected dopants to tune the wavelength response,
variation of orientation of polarization axis, and
variation of surface roughness of samples to examine the absorption dependence.

b. Feasibility Demonstration: Determine the exact coupling factors between the illumination (intensity, angle of incidence, plane of polarization etc and the photodeflection for selected sample geometries. A thorough and systemetic study of photodeflection under various illumination conditions will not only lead to a feasibility demonstration of the concept but will also establish the 'outer bounds' of the phenomenon.

c. Extension to Visible Wavelengths: The photocurrent generated in the ceramic is strongly dependent on the wavelength under a constant intensity of illumination as reported[10] earlier by Uchino et al. Suitable donor doping can shift[10] the peak response from 372 nm in $PbLa_{0.03}Zr_{0.52}Ti_{0.48}O_3$ to 384 nm m 0.9[$PbTiO_3$]- 0.1 [$La(Zn_{0.67}Nb_{0.33})$ 03]. This peak occurs near the absorption edge of the corresponding ceramic composite material. Therefore, an attempt will be made to extend the response towards the blue color region generating less deep donor -type impurity levels. The suitable candidate dopants include Mg, Ni, Co, and Cu. Also donor doping with (Nb, l's, W) with less than 1 atm% on the B site has been observed[11] to enhance the photovoltage response without compromising on the piezoelectric effect. For a solar powered mobile device this will have the effect of increasing the efficiency by 30°/0 to 50°/0 because the solar irradiance is maximum[24] at blue wavelengths. Thus by proper selection of dopants and optimization of ceramics to respond to visible wavelengths of the solar spectrum the photoactuation effect could be extended to a wider range of applications, Ceramic compounds such as $PbTiO_3$ - $Pb(A_x WY) O_3$ where A = Mg, Ni, Co, Cu will be investigated. The samples will be prepared by the conventional mixed-oxide method described elsewhere[9-11].

d. Separation of Pyroelectric and Photostrictive Effect: Preliminary observation of the photoactuation effect on typical ceramic bimorphs has indicated that consequent to light illumination at 360 nm, there is a fast response ~ milliseconds giving rise to ~ 20 microns of photodeflection followed by a slow increase in deflection possibly thermal in origin which leads to -200 micron total deflection in a matter of few seconds, The approach would be to differentiate between the two effects: electronic/electro-optic and thermal, and understand them better in order to exploit the potential of the former to obtain a fast response micromobility application.

5.2 Fabrication of Flexible Microactuator Structure: Flexible microactuator test structures would be fabricated by depositing tailored thin (2-10 micron thick) films of selected composite piezoceramic material (e.g. PLZT) films on suitably selected flexible film substrates. The key technical challenge is to obtain a tailored PLZT film well adhered to a suitable flexible substrate. This will be addressed by a three pronged approach: (a) development of a process to deposit piezoceramic thin films on high temperature polymeric substrates (such as polybenzo-oxazole) (b) lowering of crystallization temperature of PLZT and (c) delaminating films from high temperature substrates for their subsequent 'lamination' onto flexible substrates such as mylar/kapton:

a. High Temperature Polymeric Substrates:

To deposit the piezoceramic film directly onto a flexible substrate, the substrate must have high temperature stability, high strength (Young>s Modulus ~ 4.9×10^{10} N/m2), a close match of thermal coefficients of expansion with the piezoceramic film, and a tailorable crystal orient at ion in order to provide a desired template for growth of oriented PLZT. Earlier work has shown[16] that ferroelectric quality PZT could be crystallized at - 550°C. Recently[17] polybenzoxazole (PBO) has been validated at JPL to work well up to ~550°C and extensively characterized for operation at 460°C. Table 2& Table 3 provide the comparative data for a variety of substrate films and fibers. PBO stands out as the leading candidate for its high tensile strength, high Young's Modulus, low heat shrinkage and coefficients of thermal expansion and hydroscopic expansion to provide such a high temperature substrate for forming flexible microactuators by this technique. PBO is a conjugated aromatic hetrocyclic liquid crystalline polymer (LCP) with a chemical structure as shown in Figure 5.

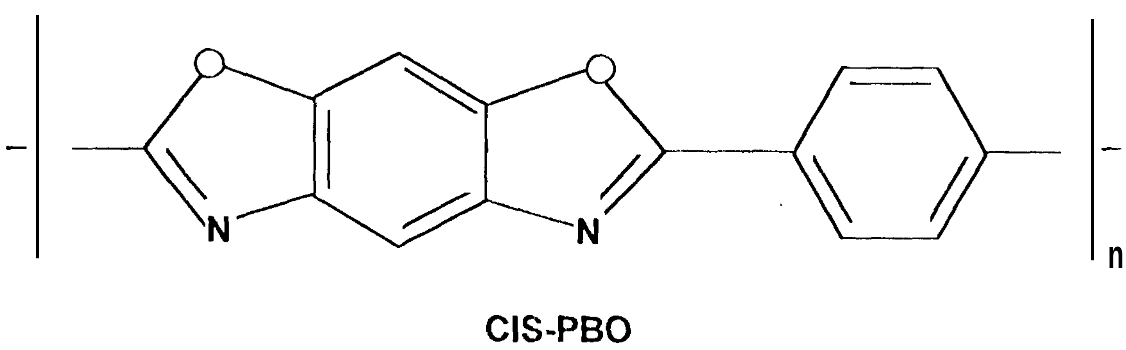


Figure 5. Chemical Structure of PBO

PROPERTY	UNIT	KAPTON	ARAMID	PET	PEN	PBO
DENSITY	g/cm^3	1.420	1,500	1.395	1.355	1.54
MELTING TEMP	°C	NONE	NONE	263	272	NoNE
GLASS TRANSITION TEMP	°C	350	280	68	113	NONE
YOUNG'S MODULUS	kg/mm^2	300	1000-2000	500-850	650-1400	4900
TENSILE STRENGTH	kg/mm^2	18	50	25	30	56-63
TENSILE ELONGATION	%	70	60-	150	95	1-2
LONG-TERM HEAT STABILITY	°C	230	180	120	155	>300
HEAT SHRINKAGE (200°C x % rein)	%	0.1	0,1	5-10	1.5	<0.1
COEFFICIENT OF THERMAL EXPANSION	ppm/°C	20	15	15	13	-2
COEFFICIENT OF HYDROSCOPIC EXPANSION	ppm/% RH	20	18	10-	10	0.8
MOISTURE ABSORPTION	%	2.9	1.5	0.4	0.4	0.8

Table 2: Comparison of a variety of polymeric, films

The chemical synthesis of PBO results in a LCP solution that is processed to fiber or film by various techniques. The high strength and superior physical properties of PBO are due to the rod-like nature of the PBO molecule and the orientation that can be built into the Polymer film. PBO film's self-reinforcing microstructure results in a "molecular fabric" with properties comparable to those of advanced, fiber-reinforced materials, but without the drawbacks of distinct fiber and matrix components. This polymer has no melting point or glass transition temperature,

PROPERTY	PBO	PBO HIGH MODULUS	ARAMID	STEEL	SPECTRA® (HDPE)	CARBON (HI-TENSILE)	GLAS (s-2)
TENSILE STRENGTH (ksi)	820	800	400-500	250	435	500-700	665
TENSILE MODULUS (Msi)	25-30	40-45	10-25	29	25	30-40	12.6
COMPRESSIVE STRENGTH (ksi)	40	65	65	250	10	300-400	>150
ELONGATION, BREAK (%)	3.0	1.5	1.5-4.0	2.0	3.5	1.5-2.0	5.4
DENSITY (g/cc)	1.56	1.56	1.44	7.86	0.97	1.8-1.9	2.4
SPECIFIC TENSILE STRENGTH (ksi)	525	510	280-350	32	450	270-380	280
SPECIFIC TENSILE MODULUS	16	26	7-18	4	26	16-22	5
LIMITING OXYGEN INDEX (LOI: %)	56	56	30		19	50-65	

Table 3: Comparative data for high performance fibers

b. Crystallization of PLZT at Lower Temperatures:

Rapid thermal annealing (RTA) using localized laser annealing to obtain crystallization of the desired piezoactive phase of PZT/PLZT at temperatures even lower than *550* C *will* be investigated. This will further reduce the constraints on the requirements of the flexible substrate, and widen the choice for selection of flexible substrates.

c. Lamination onto Selected Flexible Substrates:

i. Delamination: As an alternative technique, piezoceramic films deposited on the known high temperature substrates (e.g. alumina or silicon) would be delaminated after crystallization by controlling the adhesion of the film onto the substrate. The delaminated piezoceramic film would then be mounted/bonded onto the selected flexible substrates.

ii, Thinned Si/SiN Substrates: Another approach to be performed in collaboration with Dr. Susan Trolier Mckinstry at Penn State is to deposit the piezoceramic thin film on thinned Si/SiN wafers and then bond these structures onto the flexible substrates, During phase 1 the feasibility of using micromachined diaphragm and cantilever structures as mechanical amplifiers for thin film-based actuators in flexible structures will be determined. The approach taken here will be to fabricate the piezoelectric thin films on platinum-coated silicon substrates, micromachine them to achieve mechanically-amplified displacements, and dice out individual elements for incorporation onto the flexible substrate(with no special requirements for high temperature capability). This enables the piezoelectric film to be processed under conditions in which large piezoelectric coefficients have already been demonstrated (d33 = ***70-220*** pm/V, -d31= 80 - 100 pm/V in undoped PZT). It also eliminates problems associated with firing a polymeric substrate material at high temperatures (> 550oC in an oxidizing ambient).

An assessment of the most promising of the above three approaches will be made in phase 1 and the most promising approach pursued in Phase 2.

5.3 **Optimization of the Piezoceramic films by Mult i-Magnetron Sputtering:** The technique[16] (earlier patented by Sarita Thakoor) of multiple-sequential-target sputter-deposition, compatible with low temperature microelectronic processing, holds promise for deposition of films with tailored composition and will be extended for deposition of the multicomponent oxide piezoceramic films of lead lanthanum zirconate titanate (PLZT). This technique by providing better mixing of the components and closer control over the solid state chemical reactions during post-deposition annealing, as each individual metal layer in the deposited multilayer stack could be effectively extremely thin (even a fraction of a monolayer) provides enhanced control over the composition of the deposited film. The parameters from this multi-magnetron process can be easily extended to the JVD process for high rate piezoceramic film deposition patented by Jet Process Corporation and therefore this collaboration will allow an easy transition of the experimental process to manufacturing of flexible microact uat or structures by JPC 's manufacturing process,

The film quality improvement will be achieved by combining the following:

(a) optical quality enhancement: The defect density in a thin film could be lowered by over an order[18,19] of magnitude, thus reducing scattering losses that are common in the ceramic wafer. Figure 4 shows a comparison of the scanning electron micrograph pictures of ceramic (figure 6a) and optical quality (figure 6b) layers. Also the optical absorption coefficient in a thin film could be tailored to be almost 20 % higher than that in the bulk materials. **An order of magnitude better absorption is expected in the thin film compared to the ceramic wafer leading to a correspondingly higher efficiency**.

a b

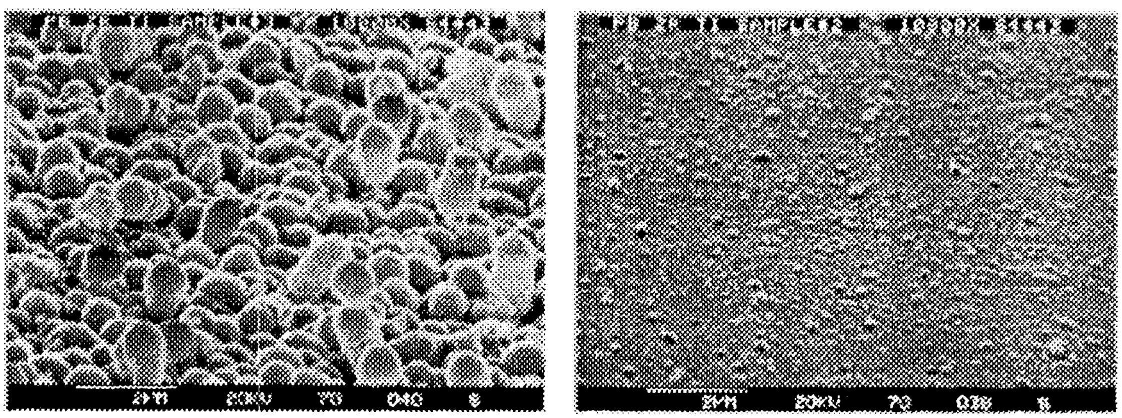


Figure 6: A comparison of the scanning electron micrographs of ceramic (figure 6a) and optical quality (figure 6b) PLZT layers,

(b) Polarization Direction and intensity Optimization: Photoresponse from ferroelectric thin films of lead zirconate titanate (PZT) is shown[20,21] to be maximum when the electric field vector associated with the incident light is parallel to the c axis in the material,

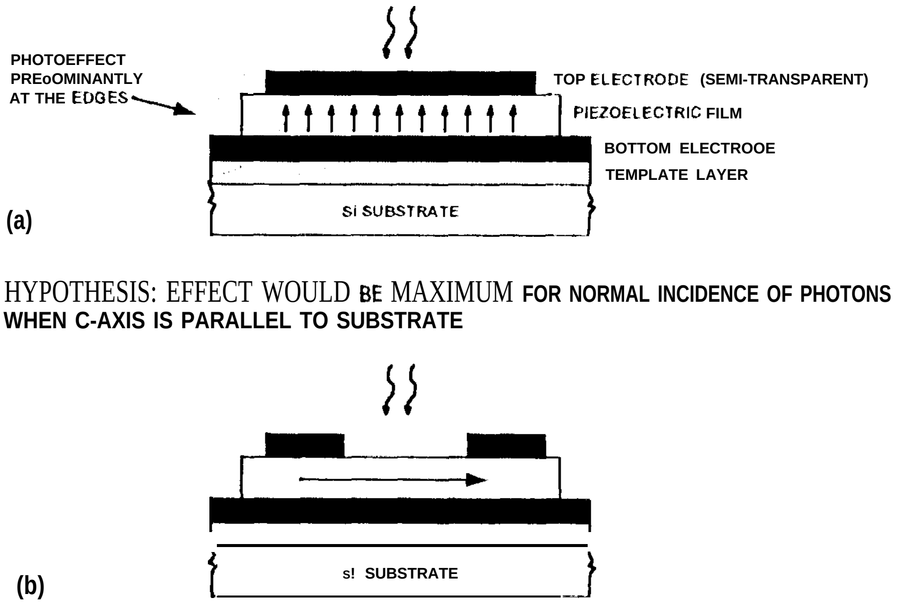


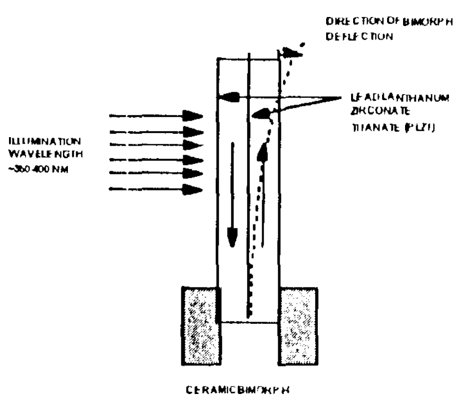
Figure 7: (a) PZT Thin film Capacitor where PZT has its c-axis oriented perpendicular to the substrate, (b) Conceptual design of a PZT capacitor with c-axis parallel to the substrate which is expect cd to maximize the photo effect,

In fact, the observed small effect from the edges of the ferro-capacitors as shown in figure 5a (with c axis predominantly perpendicular to the substrate) was primarily attributed to the domains which had some angular variation (est imat cd to be in the range of+/- 10 to 15 degrees) with respect to the substrate perpendicular. Such photoeffects are known[22] to exhibit enhancement by over an order of magnitude when the alignment of the incidence E field with the c axis changes from nominally 10 degrees to -- fully parallel. Piezoceramic PLZT is also ferroelectric and therefore the photodeflection effect is expected to be maximum when the photonic electric field is parallel to the spontaneous polarization in the ceramic (namely, the c axis,), optimization of the angle of incidence and tailoring the direct ion of spontaneous polarization in the ferroelectric will lead to maximum interaction with photon incidence and thereby maximum photodeflection. **This optimization (shown in figure 7b) will allow design of a bimorph with another order of magnitude enhancement in efficiency**.

(c) Optimization of the Optical Penetration Effect: Since the absorption of the illumination occurs in at the most 1 to 10 micron skin of the piezoelectric material facing the illumination, the photovoltage generation is expected[23] to be entirely located in this thin top skin layer, Using a film thickness equal to this penetration depth ensures that the, entire film is active. In a ceramic typically ~ *200* micron thick, almost 95 % of the bulk is an inactive mass to be moved. in films, therefore significantly larger displacements are expected.

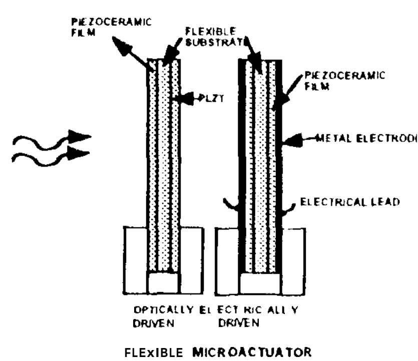
		Current Status (SOA) Ceramic Bimorph	Projected Improvement single layer film bimorph
ELECTRICAL ACTUATION PARAMETERS	**Operating Voltage**	**100 v**	**5 v**
	Force Output	**1 Kgm**	0.2 **Kg**
	Force /Power Ratio normalized to SOA	**1X**	**4X**
OPTICAL ACTUATION PARAMETERS	**Optical Power**	*80* **mW/cm²**	*8* **mW/ cm²**
	Photonic to Mechanical Energy Conversion Efficiency	**0.1** %	**1 % - 10 %**
	Force Output	**10 gm**	2 **gm**
	Force /Power Ratio normalized to SOA	**1X**	**2X**

TABLE 4: Flexible film microactuators, matrix of improvement



ceramic thickness: 200 micron

(a)



film thickness: 2 micron

(b)

Figure 8

The table 4 above shows the projected parameters of improvement. The numbers in this table are evaluated based on using a 200 micron thick typical ceramic wafer as the current state of the art and a 2 micron thick film as the flexible film bimorph projected to deliver about 20 times higher energy density (refer fig 2). Figure 8a and figure 8b compare a ceramic bimorph and a flexible film bimorph. Obtaining the optical performance enhancement will set the foundation of photonic control of mechanical motion,

5.4 **Optical Activation Study: The** exact relationship between the photovoltage, photodeflection, and the illumination intensity will be established to identify the deflection saturation point and limits of the design parameters for a mobility application, The illumination sources to be used for these photoresponse measurements include a 355 nm, compact Nd-Yag laser and a short arc (300-600nm) mercury lamp, with a spectral line filter allowing illumination at 360nm. Guided by the results of the work items 5.1 and 5.3 on optically actuated structures, thin film photostrictive materials will be prepared by the selected techniques that provide the compositional fidelity required to permit rapid prototyping of the optimized compositions of PLZT to form flexible microactuators. The amplitude and the speed of the photostrictive response will then be examined on the film bimorph versions that will be fabricated using the selected approach of **5..2.** Clearly, optimization of the flexible fim microactuators will be dictated by the results of the bulk ceramic optimization (as described in Section 5.1).

5.5 **Demonstration of Advanced Microactuation of a Film Bimorph:** An enhanced bimorph structure (Fig. 8b) will be used to demonstrate actuation triggered by both electrical as well as optical activation, One of the applications highlighted in Section 1 will be selected for demonstration of proof of concept. For example, to obtain the vibratory motion electrically, the effect is obtained by applying an alternating signal,

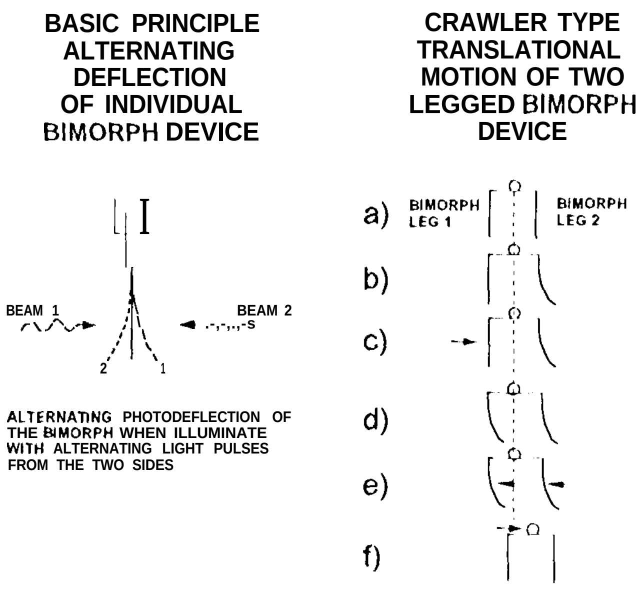


Figure 9

The vibratory motion of the bimorph will be demonstrated optically by using a two beam arrangement to alternately illuminate the two sides. The deflection measurement will be done using the optical spot deflection technique and a Polytec Inc (PI) Laser Vibrometer. The laser vibrometer utilizes a Mach Zehnder interferometer in conjunction with the Doppler shift measurements to evaluate the velocity as well as acceleration of the deflection, thereby allowing determination of force, As an example of an application, the motion sequence for a two legged crawler is illustrated in figure 9. Initially light is incident on leg # 2 from inside (left) so it moves/bends to the right. Following light incidence on # 1, makes it deflect to the right too. In the next step light is incident cm both legs from the right causing both to straighten and the head moves to the right. Electrical activation can also be used similarly to obtain the bimorph leg motion,

6. *APPLICA TIONS :*

Development of flexible microactuators which can be addressed/controlled both optically and electrically will be an enabling technology to a variety of applications in advanced micromobility (micro-mobility platforms for surveillance and security), precision micropositioning, microchopping (for *in-situ* planetary surface/environment exploration), and active control of shape/vibration/noise in flexible/membrane structures, Furthermore, remotely controlled high-precision micro-positioning is also of significant interest in medical diagnostics for precision treatment and minimally invasive access to the trauma area.

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THE ROLE OF PIEZOCERAMIC MICROACTUATION FOR ADVANCED MOBILITY

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ABSTRACT:

This paper presents a potential role of piezoceramic microactuation in micro- robotics for future space missions, e.g. unmanned sample-return missions to Mats, in search of life or evidence of prebiotic materials. The focus of the paper is on the advanced mobility with the desired characteristics of high force, displacement, and operability over a wide temperature range, at the cost of lowest possible mass, volume, and power. A comparison of the various actuation technologies including piezoceramic, shape memory alloys, polymeric actuators and magnetostrictive materials is presented. The comparison suggests piezoceramics to be the most promising candidate. A concept of flexible microactuator based on tailored films of lead lanthanum zirconate titanate, PLZT, deposited on flexible substrates is described. Such flexible microactuators are expected to offer a multifold enhancement in the force/ displacement capabilities over those of the current state-of-the-art actuators based on bulk ceramic materials. Of special interest is the promise of high efficiency actuation from an optimized thin film based flexible bimorph structure by contact-less optical activation, where the actuation will not be restricted by the clamping effect from a rigid substrate as in the current silicon based micromachined structures. Also in the current micromachined structures, the actuation force out of the structure is limited by the thickness to which the micromachined structures could be grown. Deposition of thicker piezoceramic thin films on flexible substrates would not only virtually eliminate the substrate clamping effect, but also would result in substantially higher force to input power ratio. Flexible microactuators would form an enabling framework for a new class of small vehicles (insect explorers), with advanced mobility and dedicated sensing ability, emulating the agile characteristics of insects. In addition to the space exploration, such small insect explorers with their ability to explore hard-to-reach terrain would be ideal for a variety of applications in law enforcement, inspection of hazardous environment, search and rescue in disaster areas such as earthquake sites etc. Additionally the flexible microactuators would also be useful for high precision surgery or minimally invasive medical diagnostics, optical micropositioning, solar tracking actuator/shutter, direct corrective control in adaptive optics/interferometry, and photophones.

1. INTRODUCTION

1,1 Advanced Mobility for In-situ Space exploration:

In-situ, autonomous exploration and intelligence gathering from surfaces, subsurfaces, and environments will benefit from a totally new class of exploring vehicles: small in size, mobile and agile like insects, equipped with dedicated microsensors. For example, a mission to Mars for retrieval of significant samples in search of life extinct or extant or evidence of prebiotic materials could be a target application, Large number of such inexpensive, therefore dispensable and low risk explorers would supplement the functions performed by traditional exploration modes. Furthermore, their dedicated sensing functions and small size would be invaluable in hazardous or difficult-to-reach territories for scouting missions. Onc approach for realization of such vehicles is evolutionary: through the miniaturization of existing wheeled vehicles, Another approach with significant potential advantages, especially when traversing unusual and difficult terrain such as loose granular surfaces, is to imitate the mobility attributes of insects. Mimicking biology, such artificial insects may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration. They would combine the functions of advanced mobility and sensing with a choice. of electronic and/or photonic control. I'reprogrammed for a specific function, they could serve as "no-uplink, one-way communicating" beacons, spread over the exploration site, autonomously looking for the object of interest,

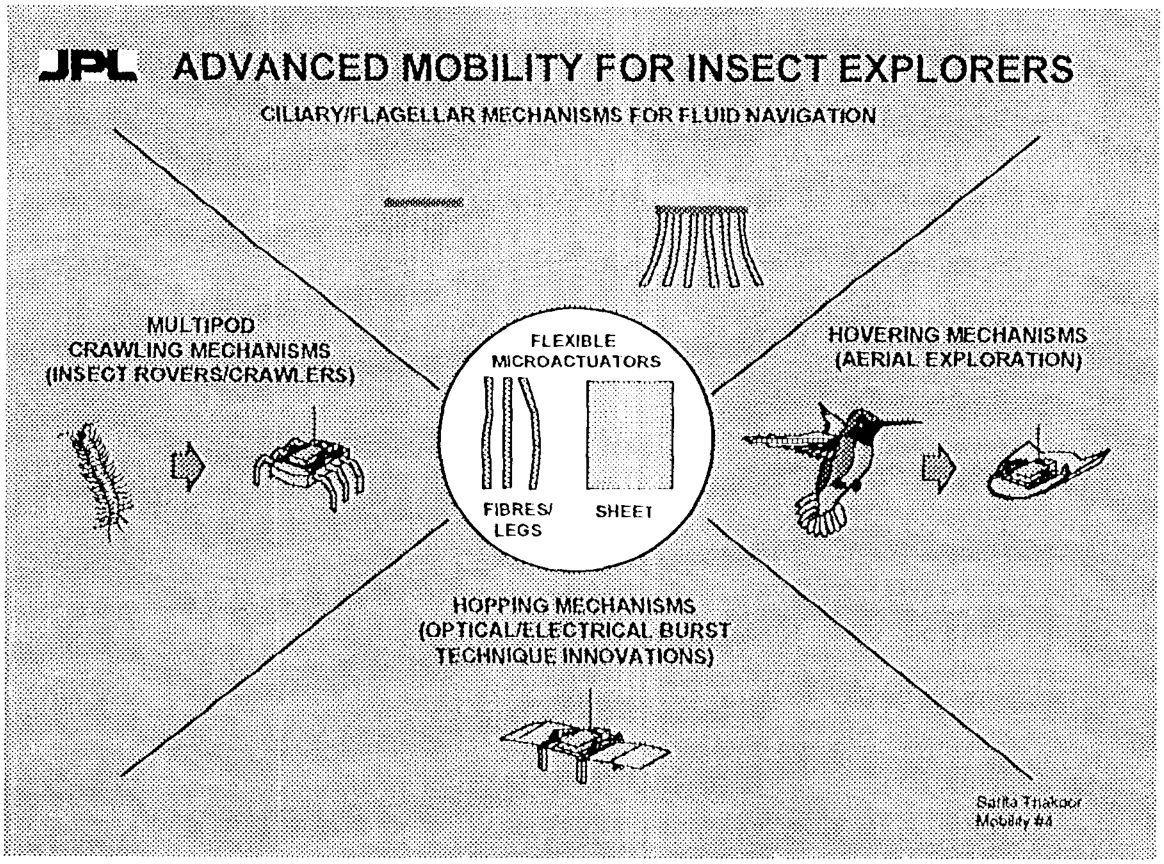


Figure 1

A breakthrough in actuation technology is required to realize the variety of advanced mobility mechanisms for such "insect explorers". ***Flexible microactuators must provide a high displacement and force combination with low power consumption, and must work over wide temperature ranges.*** Figure 1 illustrates four different kinds of insect explorers/in-situ explorers[1] emulating biological mechanisms:

A. Multi pod crawlers/burrowers for surface/subsurface explorations maneuvering through soft soil and difficult terrain, adaptive to the environment.

B. Ciliary / Flagellar Explorers for navigation through fluids (for e.g. under water exploration for Naval applications)

C. Hopping Mechanisms for surface and aerial exploration

D. Hovering Explorers for aerial exploration

Flexible microactuators that could be addressed/controlled optically and/or electrically would be an enabling technology for insect -explorers. In turn, due to their promise for exploration of difficult, hard to reach terrain, insect explorers will be ideal for a variety of applications including law enforcement, inspection of hazardous environment, search and rescue in disaster areas such as earthquake sites. Additionally such flexible manipulation could also be used for high precision surgery or minimally invasive medical diagnostic tools, optical micropositioning, solar tracking actuator/shutter, direct corrective control in adaptive optics/interferometry, and photophones.

1.2 INSECT EXPLORERS: Key Features

A. Multiple explorers with dedicated functions: Multiple explorers would allow widespread coverage of a selected exploration site. The stringent requirements on precision landing at selected site thereby would be relaxed. Their significant function would be in-situ sensing and atmospheric information gathering combined with localized surface exploration at the landing locale of the explorer. Consider the specific function of life sensing or resource scouting for mining purposes cm unexplored planets. Life sensing could include sensing for prebiotic material such as amino acids, sensing for water or identifying carbonates as evidence of extinct /extant life. Innovative state-of-the-art sensors such as for individual gases, elements, specific amino acid assay, radiation monitor etc can be packaged in small volumes and mounted on such miniature mobile platforms such as the insect-Explorer, Sensing for specific gases, elements, or radiation might suffice for resource scouting.

B. Low cost, expendability of individual explorers: individual explorers need to be expendable; loss of a single explorer will not mean loss of a whole suite of instruments. Higher risk exploration of hazardous sites, and new site scouting can be done using these explorers. This need for low cost insect explorers for planetary exploration becomes specifically crucial in light of the challenge we have for human and robotic missions for exploration of the solar system by developing affordable, new exploration concepts and techniques.

C. **Low n]ass/size, greater maneuverability: Advanced mobility needs to be low mass/size operable at low power so that such insect explorers** can be easily accommodated in the mass reserves of the mission and will allow exploration of hard to reach, noı really inaccessible or hazardous locations. The advanced mobility mechanisms employed will allow negotiating soft soil and traversing over or around boulders

1). **Science return relative to the cost investment would be tremendous:** Dedicated in-situ sensing can be achieved at a vet y low cost with low risk in a widespread area with gı eater local access. Both surface/subsurface exploration & atmospheric information gathering - is attainable by the entire swarm of explorers consisting of all the different mobility kinds put together. Furthermore, the small size allows it to approach the subsurface through wide cracks/crevices and thereby sample non-in **vasively** pristine materials hidden underneath.

E. **Environmentally reliable - wide temperature range of operation :** The use of robust actuators with good cyclability and a wide temperature range of operation is required.

II. FLEXIBLE MICROACTUATORS:

The emerging field of nlicro-clcctro-mechanical systems (MEMS) and micro-opto-mechanical systems (MOMS) holds a promise of revolutionary developments for DoD applications ranging from autonomous mobility platforms (micro- Unmanned Aerial Vehicles), medical diagnostic tools to petaflop computing. On the other hand, NASA's vision of future microspacecraft entails reduction in size of all spacecraft components by orders of magnitude. A breakthrough in actuation technology is required to obtain such size reduction for the next gene.ration DOD and NASA micromobility applications. in the commercial application area, there is an urgent need to miniaturize the size of end- effecters on the medical diagnostic t ools such as micro-catheters or endoscopic manipulators, to enable minimally invasive surgery without compromising the mobility and flexibility,

11.1 Current Status: Flexible Actuators

Polymeric actuators[2] based on polyvinylidene difluoride (PVDF) and polymethyl-m ethacrylate (PMMA), although proven for tactile sensing and some high strain applications, have been used with limited success for mobility applications duc to their limited force capacity and restricted temperature. range of operation and therefore limited cyclabilit y. Some recent[3,4] work on isodactic PMMA has reported high displacements, although the exact nature of the observed effect (coulombic or electrostrictive) and its cyclability with temperature, arc matters of continuing research. Therefore, its potential for providing high strain/force combination and useful **work** over a wide t emperature range is unclear. ionic conduct ing pol ymer gel films (ICPF) discovered by Oguro ct al[5] in 1992 have received substantial attention to-date[6,7]. However, the response speed of t hcsc act uators is rather slow (several seconds), the drive current is high, temperature range of operation is limited, and they work only in aqueous medium, There is a need for flexible microactuators that could provide a high strain and force combination for low power consumption, and could operate over a wide temperature range for the variety of advanced mobility applications identified above.

11.2 {comparison of Actuation Technologies:

l'able 1 presents a comparison of the different actuation technologies and illustrates why piezoceramics arc the leading candidate, especially when dimensions shrink and approach those of thin films, where properties arc generally tailorable by fine composition control. Thin film growth techniques through their close control cm composition allow a much finer control of hysterisis and aging properties. in particular, the lower holding power requirement by piezoceramics makes them attractive over magnetic actuators which suffer from the need for significant heat dissipation, With size reduction, the energy absorbed by piezoceramics could be upto two orders of magnitude higher[8] compared to electrostatic and magnetic. actuators (Figure 2). This higher density is attributed to the higher dielectric constant of the piezoceramics and the increasing breakdown field with reducing thickness[8]. Furthermore, piezoceramics offer the potential of solar driven, tetherless mechanisms since they can be actuated[9-11] directly by optical illumination (350nm to 450 rim). Piezoceramic actuation is potentially robust, amenable to low temperature (deep space) operation, and intrinsically radiation-resistant. In addition, their ability to be batch-produced by thin film manufacturing technique.s on large substrate areas offers convenience and cost effectiveness.

WHY PIEZOCERAMIC ACTUATION?

(AS WE SCALE DOWN TO THIN FILM PIEZOCERAMICS)

			POLYMERIC MATERIALS		
	PIEZOCERAMIC	SHAPE MEMORY ALLOY	PVDF	Polymides PMMA Polyurethanes	MAGNETO-STRICTIVE
MECHANISM	PIEZOELECTRIC & ELECTROSTRICTIVE	THERMAL: MARTENSITIC -> AUSTENITIC PHASE CHANGE	PIEZOELECTRIC PHASE TRANSIT	ELECTRO-STRICTIVE	MAGNETIC FIELD INDUCED BY COI
STRAIN	10^{-4} TO $0.3X10^{-2}$**	10^{-3} TO 10^{-1}	10^{-3} TO 10^{-1}	10^{-4} TO 10^{-2}	10^{-6} TO 10^{-2}
DISPLACEMENT	LOW TO HIGH*	MEDIUM TO HIGH***	LOW TO HIG	LOW TO MEDIUM	MEDIUM
FORCE	HIGH ~100 kgm FORCE	LOW-MEDIUM ~1 kgm FORCE	SMALL	SMALL	HIGH
HYSTERISIS	TAILORABLE BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	LARGE
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	-196°C -> 300°C WIDE	-196°C -> 100°C WIDE	-10°C -> 60°C LIMITED	-10°C -> 80°C LIMITED	-273°C -> 100°C WIDE
RESPONSE SPEED	µsec-msec	seconds	msec	msec	µsec-msec
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	LOW	LOW	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	YES	TBD	TBD	TBD	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR-POOR	GOOD
PROSPECT OF MINIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAIR

PIEZOELECTRICS REPRESENT A LEADING CANDIDATE FOR ADVANCED MICROACTUATION

* With amplification techniques (e. g. optically or electrically activated bimorph, flextensional elements and combination thereof to obtain double amplification)

** Anti ferroelectric phase transition materials

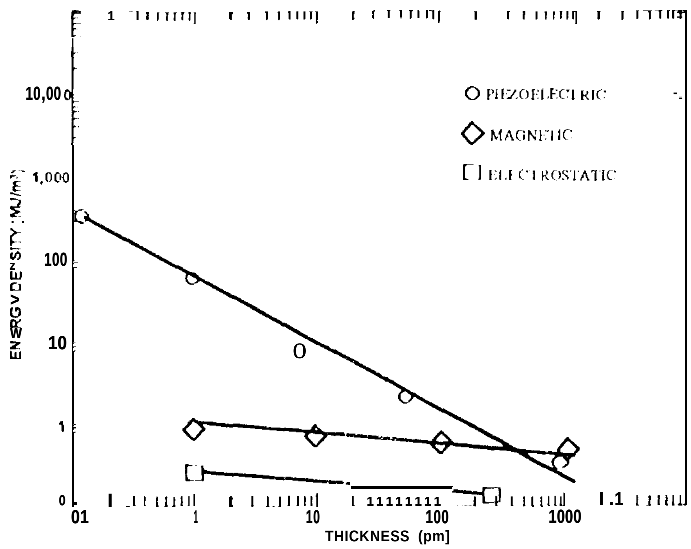
*** Limited by Thermal Energy Input

Table 1

It is apparent from the above comparison table that piezoceramics represent a leading candidate for advanced microactuation specifically in light of the requirements of futui c space missions,

11.3 Electrically Activated Piezoceram ic Actuation:

The electrically activated piezoceramic actuation based on tailored bulk materials is well established and used in several applications. However, the high voltage (>100 V) required for piezoceramics is undesirable as the actuators scale down in size. Flexible microactuators on the other hand based on tailored thin films (- 2 micron thick) deposited on selected flexible substrates promise substantially higher (~25 times) energy density, compared to a 200 micron thick ceramic wafer, and therefore could be operated even at as low as 5 V to provide five times enhanced force pcr unit volume. Application of Si-VLSI compatible signal of 5 V is clearly quite convenient, and the five times enhancement in applied field would directly result in **5 X** enhancement in the force output from the device per unit volume. Moreover, due to the lower power consumption (extremely low holding current), the **2** micron film microactuator is extremely attractive to implement.



Energy density as a function of film thickness
Figure 2

11.4 Optically Activated **Piezoceramic Actuation:**

Two oppositely poled lead lanthanum zirconate titanate (PLZT), ceramic wafers bonded together to form a piezoceramic bimorph (as shown in fig 4a) exhibit a large photodeflection, analogous to a piezoelectric bimorph. Essentially the differential strain in the **two oppositely poled** wafers gives rise to a large deflection of the bimorph clement. A deflection as high as -200 micron, away from the direction of the light, has been obtained from a bimorph ~2 cm long, ~0.5 cm wide, and ~0 4 mm thick, when exposed to an intensity of ~80mW/cm^2. in such a deflection, a force of ~10 gm is generated at the tip of the bimorph. in fact, PLZT ceramic wafers have been earlier used[13,14] to demonstrate two different kinds of mobile walking and gripping devices based on such photoactuation in ceramics. However the limited photonic energy to mechanical conversion efficiency (- O,]°/.) obtained in the ceramic due to its poor optical quality left those demonstrations as mere curious experiments. ***With the recent emergence of thin film growth techniques for piezoceramic PLZT films, a new opportunity has arisen in exploiting the full potential of this optical actuation effect for photonic control of mechanical motion***. As detailed in the next section, optimization of the material with respect to its defect density, absorption coefficient, spontaneous polarization direction, and bimorph geometry (aspect ratio, etc.) could lead to a substantial (up to two orders of magnitude) enhancement in the photoactuation efficiency. A flexible PLZT film microactuator thus enhanced, clearly would bypass the need for an electrical energy source, and open up numerous possibilities of deployable, optically triggered, contactless actuators, and even solar power driven advanced mobility.

Clearly, such *advanced mobility (ciliary/flagellar mechanisms, multipod inchworm/crawling mechanisms)* ***would*** be t etherless, and either autonomous or remote-controlled. The prohibit ive weight and mobility restrictions due to an umbilical power cord would be eliminated. The photogenerated deflection could be used to directly "walk" on the surface or to run motors for indirect locomotion Such tetherless optical control of advanced mobile vehicles would also be desirable for exploration of hazardous, hard to reach locations, as long as at least a line of sight exists, Piezoceramic bimorphs provide a good trade of load versus displacement for piezoceramics and have been used for a variety of applications, optically driven bimorphs have a similar niche for applications requiring high displacement and low load requirement with the added versatility of photonic addressing.

III. FLEXIBLE MICROACTUATORS: POTENTIAL BENEFITS/UNIQUE FEATURES

Flexible microactuators arc envisioned by depositing tailored thick (- 2-10 micron) films of fictive materials on strong flexible (polymeric) substrates. **Flexible microactuators inherently would provide a combination of high force and displacement and be operable over a wide temperature range**. Potential advantages of flexible microactuators are:

- low power (low voltage operation, <5 V), low mass, low volume
- **low** cost, batch production of the components compatible with VLSI processing
- high force/volunlc even with low voltage operation
- higher deflection
- flexible, miniaturizable microactuator: scaleable for MEMS/MOMS
  excellent cyclability -more than million cycles
  amenable to both electrical or optical activation

A schematic of such a flexible actuator is illustrated in figure 3b. It can be formed in the form of fibers or sheets (figure 1).

in addition to the high energy density offered by piezoceramic thin films (up to five times enhanced ratio of output force per unit volume for a film bimorph with operation at the Si-VLSI compatible low voltage of 5 V), they promise two to three orders of magnitude enhanced conversion efficiency (as described in next section) in a piezoceramic **flexible** bimorph **when**

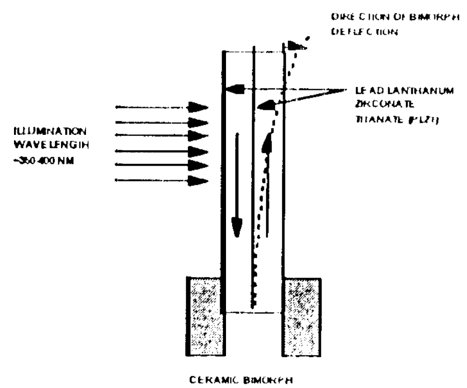
activated optically accompanied with upto two hundred times higher ratio of output force to input power. Specifically optical control has following advantages:

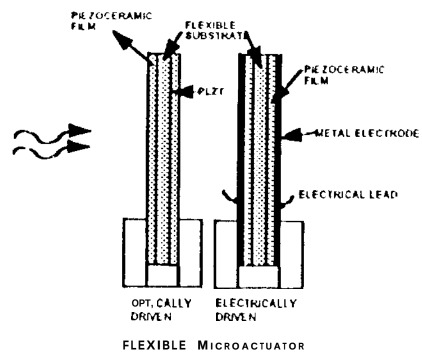
- contactless control/remote control
- low power solution
- electrode-less, contact less structure
- enhanced reliability, external voltage not required (breakdown issues avoided)

microdisplacement proportional and controllable by the intensity of the light energy

Such flexible microactuators would enable a new generation of non-silicon based microelectro- mechanical and micro-opto-mechanical mobility systems where the actuation will not be restricted by the clamping effect due to the rigid substrate as in the current silicon based micromachined structures. Also in the current micromachined structures, the actuation force out of the structure is limited by the thickness to which the micromachined structures could be grown. Deposition of tailored piezoceramic thin films on flexible substrates would substantially eliminate the substrate clamping effect and thicker films can be deposited by high rate deposition processes, leading to mobile elements with substantially higher force to input power ratio.

IV. FLEXIBLE MICROACTUATORS: PROJECTED PERFORMANCE





ceramic thickness: 200 micron film thickness: 2 micron

(a) **(b)**

Figure 3

Figure 3a and figure 3b compare a ceramic bimorph and a flexible film bimorph. The table 2 below shows the projected parameters of improvement. The numbers in this table are evaluated based on using a 200 micron thick typical ceramic wafer as the current state of the art and a 2 micron thick film as the projected flexible film bimorph. Such a film bimorph activated with 5 V will have ~ 25 times higher energy density than the ceramic bimorph that requires ~ 100 V. In turn, although the net force output from the bimorph will be 20% of that from the ceramic, the force /volume will be five times higher. (correspondingly, in the case of optical actuation, optimization of the material with respect to its defect density, absorption coefficient, optical quality, spontaneous polarization direction, and bimorph geometry could lead to a substantial (up to two orders of magnitude) enhancement in the photoactuat ion efficiency and thereby allow exploitation of the full potential of the optical actuation effect for photonic control of mechanical motion. Such a flexible, optically triggered microactuator would eliminate the need for an on-board electrical energy source, and open up numerous possibilities of small, light-weight, deployable, optically triggered, contactless actuators, and even solar power driven advanced mobility. Due to the enhancement in conversion efficiency (expected value - (10/0 - 10%), the optically activated film bimorph is projected to deliver force output 2-20 times that of the ceramic This is expected with illumination intensity an order magnitude lower than that currently used for the ceramics. This will result in an enhancement of force per unit power by 20 to 200 times. Obtaining the optical performance enhancement in input photonic power to output mechanical force will as indicated provide a substantially enhanced bimorph

		Current Status Ceramic. Bimorph	Projected Improvement Film Bimorph
ELECTRICAL ACTUATION PARAMETERS	Thickness	200 microns	2 microns: Thickness reduced, material tailored
	Operating Voltage	100 V	5 V : Operational voltage reduced
	Energy Density	1 X	25 X : Inherent advantage of reduced thickness
	Force/Energy	5F	F
	Force/Volume	1X	5X enhancement for film bimorph
OPTICAL ACTUATION PARAMETERS	Optical Power	80 mW/cm^2	8 mW/ cm^2 : Illumination Intensity reduced by 10 times
	Power Ratio	10X	1X
	Photonic to Mechanical Energy Conversion Efficiency	0.1 %	1 % - 10 % : significant enhancement in overall efficiency
	Force /Energy	F	2F to 20F : Multifold enhancement in the film bimorph
	Force /Power	1X	20X to 200X

TABLE 2: Flexible film microactuators, matrix of improvement

V. CONCLUSION:

The new concept of piezoceramic flexible microactuators described in this paper offers a combination of high force and displacement with potential of operability over a wide temperature range and a contact-less optical activation, Piezoceramic based flexible microactuators would form an enabling technology for a variety of applications including advanced mobility, shape control, microvalves and minimally invasive precision medical treatment/diagnostics.

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CL-96-1430 9/13/96

THE ROLE OF PIEZOCERAMIC MICROACTUATION FOR FUTURE JPL MISSION APPLICATIONS

JPL

Sarita Thakoor, J. M. Morookian, and J. A. Cutts

August 20, 1996

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91109

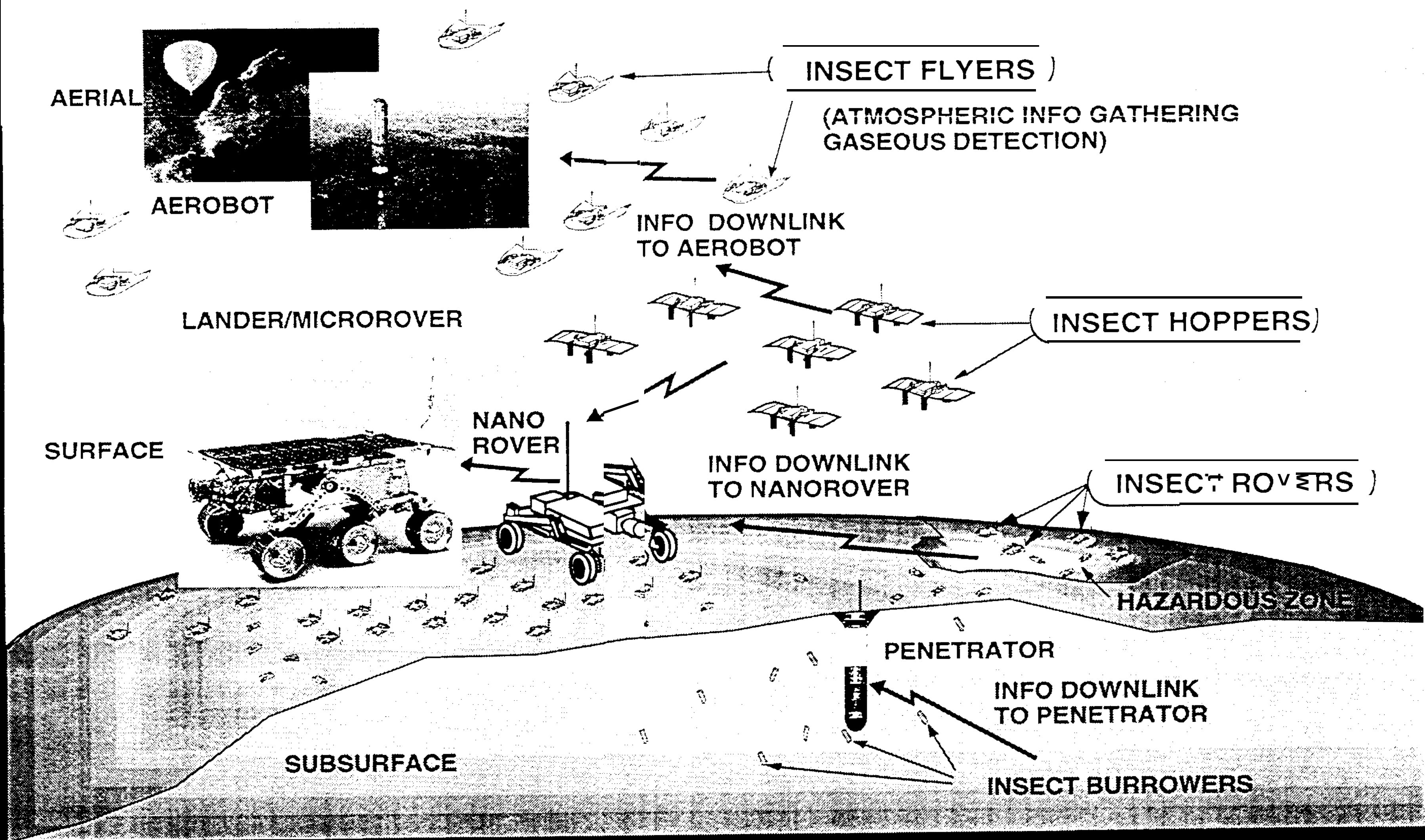
10th International Symposium on Applications of Ferroelectrics, Aug 18-21, 1996; New Jersey

OUTLINE

- MOTIVATION
- WHY PIEZOCERAMICS
- APPROACH
  - FLEXIBLE MICROACTUATORS
  - ELECTRICAL/OPTICAL ACTIVATION
  - ENHANCED BIMORPH: LOW POWER, HIGH FORCE
- APPLICATIONS
  - ADVANCED MOBILITY
  - OPTICAL SHAPE CONTROL
  - MICROVALVES
  - PRECISION MEDICAL TREATMENT/DIAGNOSTICS
- CONCLUSIONS/ SUMMARY

INSECT EXPLORERS

HIERARCHICAL ORGANIZATION: ALLOWS COMPOSITE, AFFORDABLE EXPLORATION OF THE SOLAR SYSTEM



SARITA THAKOOR
VISION 01

VISION:

ADVANCED MOBILITY . . . . . . the size of small insects

..*..** with the same mobility, agility

When coupled with dedicated microsensors/ microimagers -

INSECT EXPLORERS

They will be ideal for:

- SCOUTING MISSIONS - IN-SITU SENSING
- HAZARDOUS AREA EXPLORATION
- REACH NARROW CREVICES

Such “artificial” insects will enable that couldn’t be easily done today

PAY_OFF - WHY INSECT EXPLORERS

- Extremely small size - allows reach to places never reached before for in-situ sensing
- Expendable due to low cost - will be used to explore high risk zones
- Science return/$ would be tremendous, unprecedented.

TO REALIZE THE VISION:

ACCOMPLISH IT IN SIGNIFICANTLY LESS TIME THAN NATURAL EVOLUTION TOOK FOR INSECTS - ADVANCED NANOACTUATION TECHNOLOGY

NATURE'S INSECTS: COMPLEX MULTIFUNCTIONAL MULTI SYSTEM
EXQUISITE MARVELS CREATED IN MILLIONS OF YEARS

INSECT EXPLORERS: SIMPLE, SINGLE DEDICATED FUNCTION ATTAINABLE IN ~ 10 YRS
WITH FOCUS INITIATING TODAY ON NEW TECHNOLOGY INNOVATIONS
TO OBTAIN . . . . **ADVANCED MOBILITY**

WHY PIEZOCERAMIC ACTUATION?
(AS WE SCALE DOWN TO THIN FILM PIEZOCERAMICS)

			POLYMERIC MATERIALS		
	PIEZOCERAMIC	SHAPE MEMORY ALLOY	PVDF	Polymides PMMA Polyurethanes	MAGNETO-STRICT-WE
MECHANISM	PIEZOELECTRIC & ELECTROSTRICTIVE	THERMAL MARTENSITIC → AUSTENITIC PHASE CHANGE	PIEZOELECTRIC, PHASE TRANSITION	ELECTRO-STRICTIVE	MAGNETIC FIELD INDUCEI? BY COIL
STRAIN	10^{-4} TO $0.3X10^{-2}$**	10^{-5} TO 10^{-1}	10^{-6} TO 10^{-1}	10^{-9} TO 10^{-2}	10^{-5} TO 10^{-2}
DISPLACEMENT	LOW TO HIGH*	MEDIUM TO HIGH***	LOW TO HIGH	LOW TO MEDIUM	MEDIUM
FORCE	HIGH ~100 kgm FORCE	LOW-MEDIUM ~1 kgm FORCE	SMALL	SMALL	HIGH
HYSTERISIS	TAILORABLE BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	LARGE
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	–196°C → 300°C WIDE	-196*C → 100°C WIDE	–10°C → 60"C LIMITED	–10°C → 80°C L! MITED	-273°C → 100"C WIDE
RESPONSE SPEED	µsec-msec	*seconds*	msec	msec	µsec-msec
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	LOW	LOW	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	YES	TBD	TBD	TBD	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR-POOR	GOOD
PROSPECT OF M INIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAIR

PIEZOELECTRICS REPRESENT A **LEADING** CANDIDATE FOR ADVANCED **MICROACTUATION**

* With amplification techniques (e. g. optically or electrically activated bimorph, flextensional elements and combination thereof to obtain double amplification)

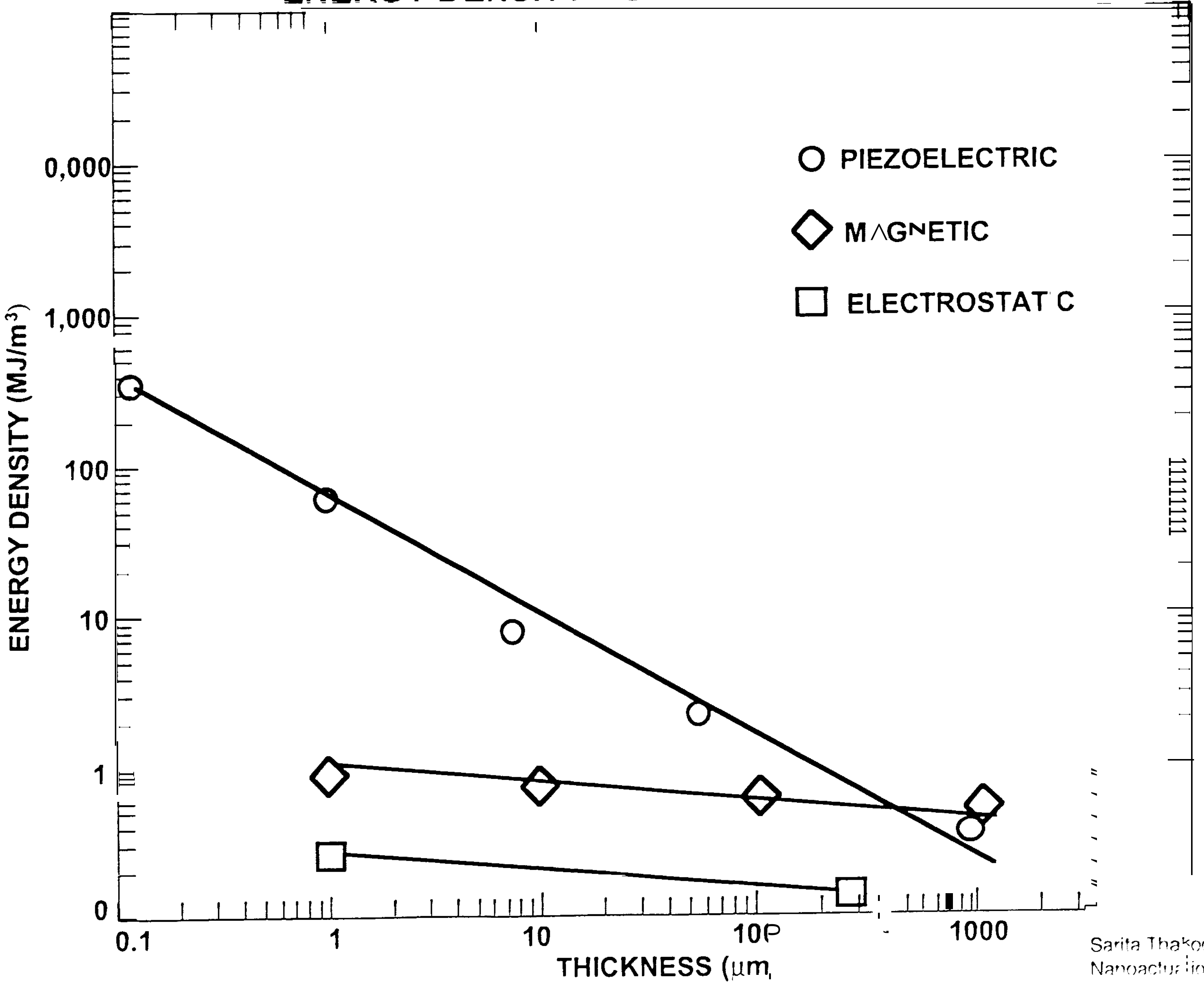
" Antiferroelectric phase transition materials

*** Limited by Thermal Energy Input

Sarita Thakoor
isaf96 7

COMPARISON ACTUATION TECHNOLOGIES

ENERGY DENSITY AS FUNCTION OF THICKNESS



Sarita Thakoor
Nanoactuation

JPL

FLEXIBLE MICROACTUATORS

Flexible microactuators are envisioned by depositing tailored thick (-- 2-10 micron) films of active materials on judiciously chosen, strong flexible (polymeric) substrates. Flexible microactuators would provide a combination of high force and displacement and be operable over a wide temperature range as is required for a variety of advanced mobility applications. Potential advantages of flexible microactuators are:

- low power (low voltage operation, < 5 V), low mass, low volume
- high force/volume even with low voltage operation
- higher deflection
- flexible, miniaturizable microactuator: scaleable for MEMS/MOMS
- excellent cyclability -more than million cycles
- amenable to both electrical or optical activation

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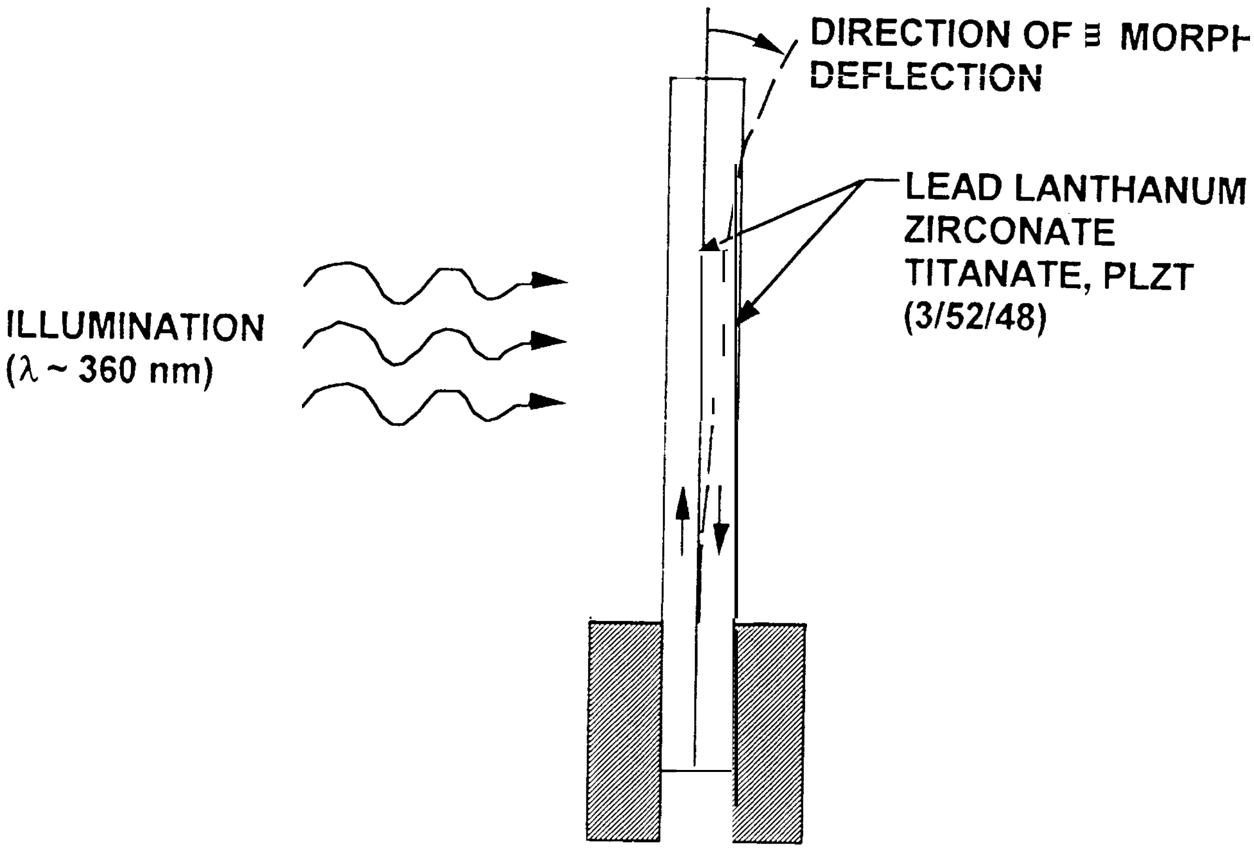
FLEXIBLE MICROACTUATORS

Flexible microactuators would enable a new generation of **non-silicon** based **microelectro-** mechanical and micro-opto-mechanical systems **where the actuation will not be restricted by the clamping effect due to the rigid substrate as in the current silicon based micromachined structures.** Also **in the current micromachined structures, the actuation force out of the structure is limited by the thickness to which the micromachined structures could be grown. Deposition of tailored piezoceramic thin films on flexible substrates would substantially eliminate the substrate clamping effect and thicker films can be deposited by high rate deposition processes, leading to mobile elements with substantially higher force to input power ratio with the option of contact-less optical activation.**

JPL PHOTODEFLECTION OF PLZT BIMORPH



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Jan, 1995

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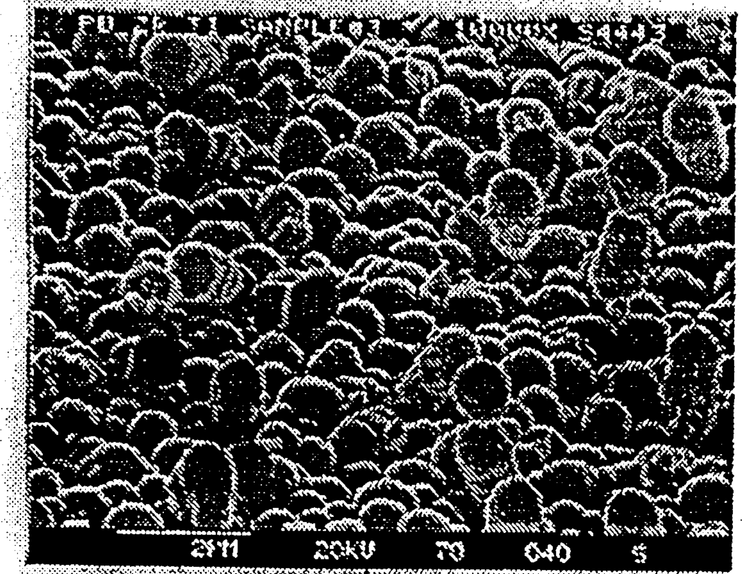
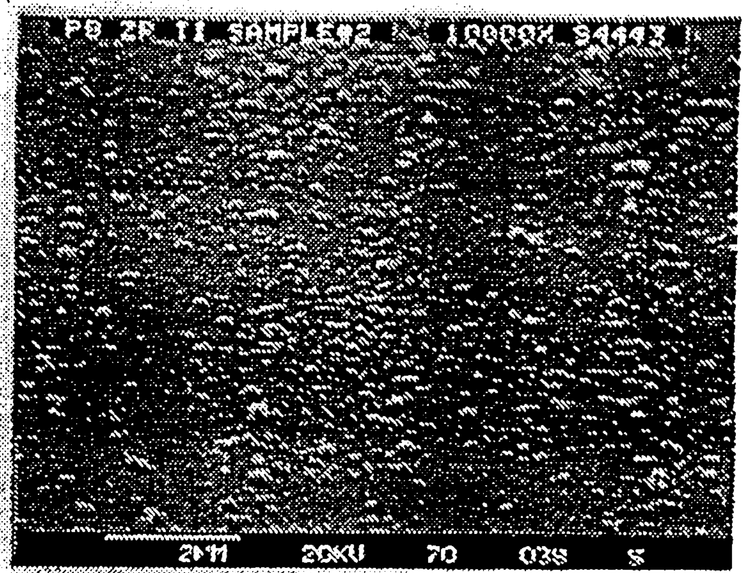
FLEXIBLE MICROACTUATORS

- Optimization of the Piezoceramic films:
  - Optical quality enhancement
  - Polarization direction& intensity optimization
  - Optimization of the optical penetration effect

a



b



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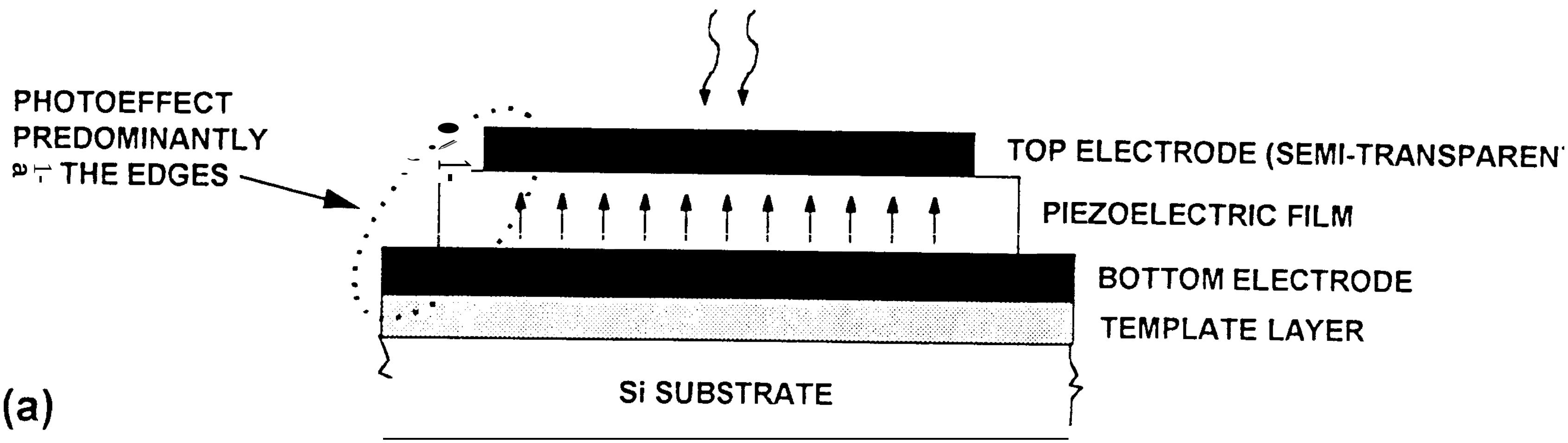
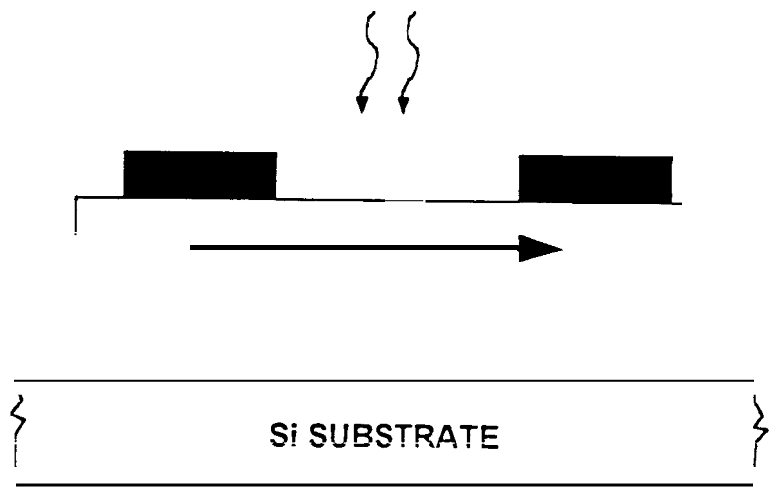


(a)



(b)

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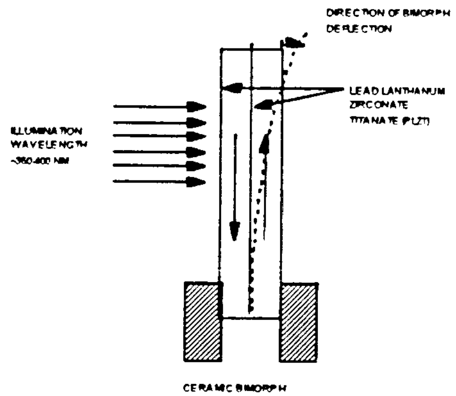
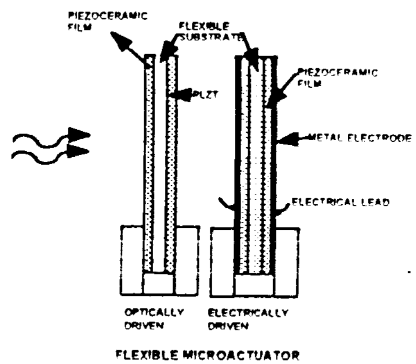


ceramic thickness: 200 micron

(a)



film thickness: 2 micron

(b)

JPL

TABLE 4: **Flexible film microactuators,** matrix of improvement

		Current Status Ceramic Bimorph	Projected Improvement Film Bimorph
ELECTRICAL ACTL'A'TIOA' **PARAMETERS**	**Thickness**	**200 microns**	**, 2 microns: Thickness reduced, material tailored**
	Operating Voltage	**100** *v*	**5 V : Operational voltage reduced**
	Energy Density	' *l x*	**25 X** *:* **Inherent advantage of reduced thickness**
	Force/Energy	**5F**	**F**
	Force/Volume	l x	**5X enhancement for film bimorph**
OPTICAL ACTUATION PARAMETERS	**Optical Power**	**SO mW/cm^2**	**8 mW/ cm^2 : Illumination Intensity reduced by 10 times**
	Power Ratio	lox	l x
	Photonic to Mechanical Energy Conversion Efficiency	**0.1 %**	**1 % -** 10 **0/0** : **significant enhancement in overall efficiency**
	Force /Energy	**F**	**2F to 20F : Multifold enhancement in the film bimorph**
	Force /Power	*1x*	*20X* **to 200X**

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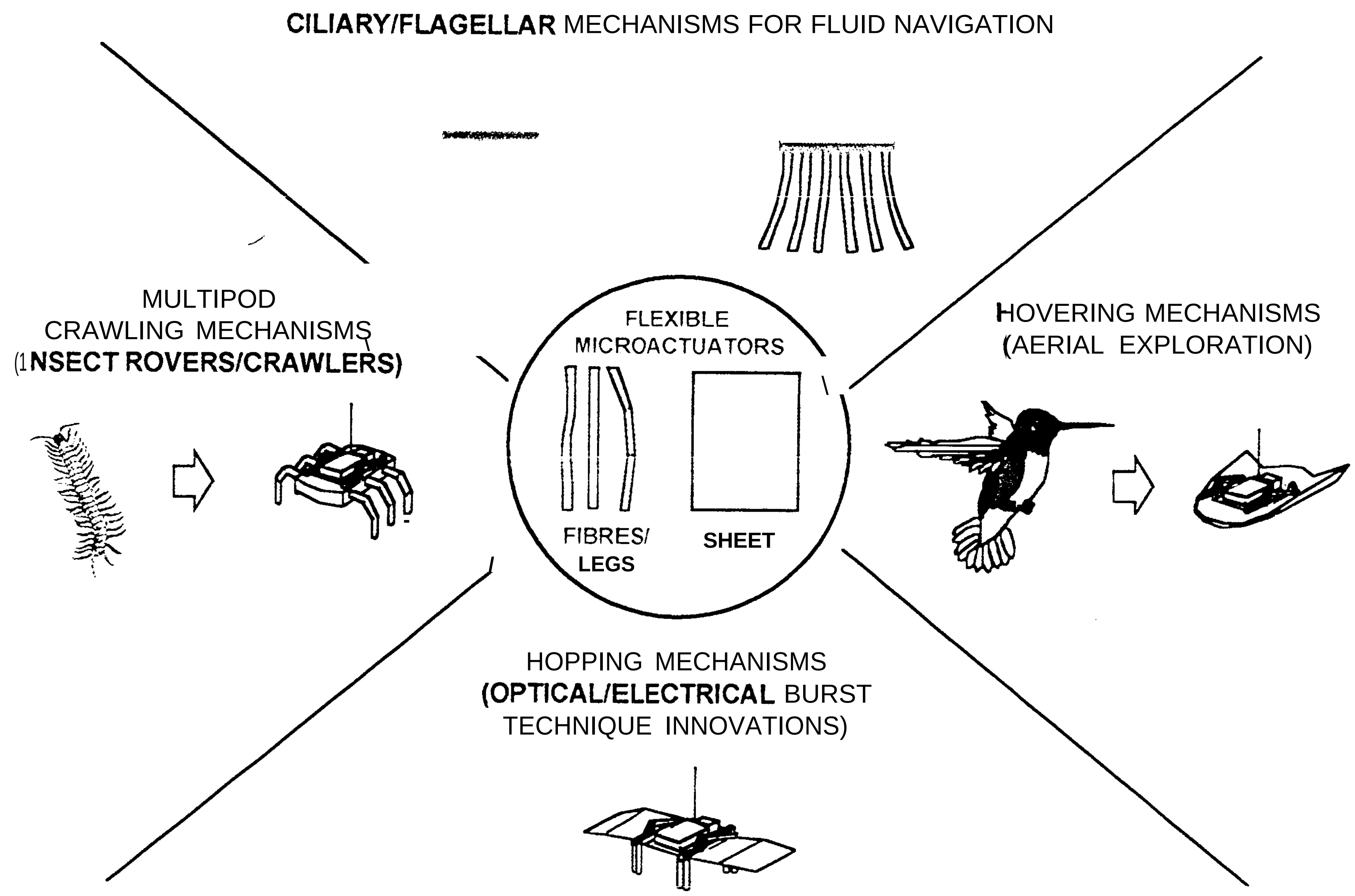
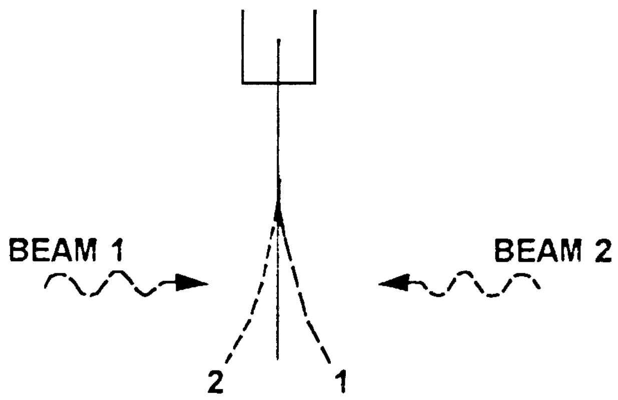
JPL ADVANCED MOBILITY FOR INSECT EXPLORERS



Sarita Thakoor
Mobility #4

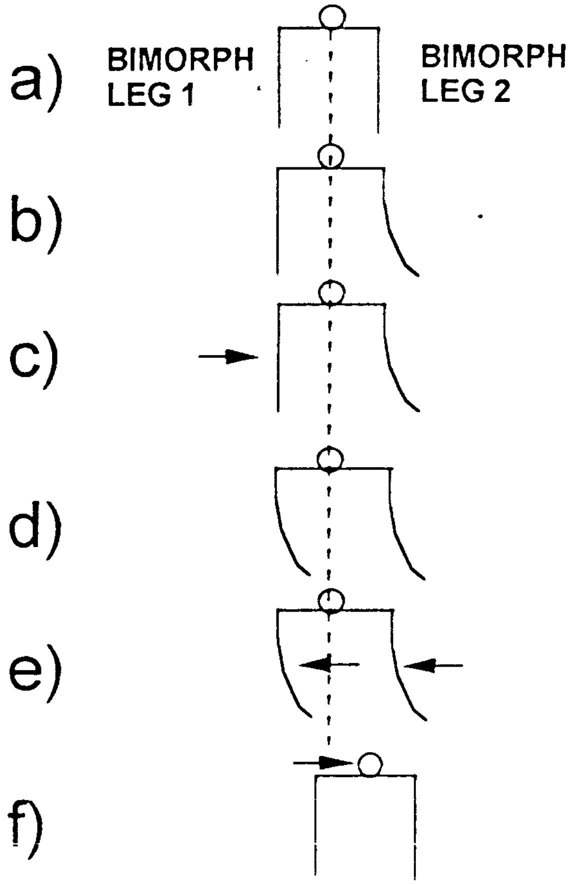
PHOTODEFLECTING BIMORPH DEVICE

BASIC PRINCIPLE ALTERNATING DEFLECTION OF INDIVIDUAL BIMORPH DEVICE



ALTERNATING PHOTODEFLECTION OF THE BIMORPH WHEN ILLUMINATED WITH ALTERNATING LIGHT PULSES FROM THE TWO SIDES

CRAWLER TYPE TRANSLATIONAL MOTION OF TWO LEGGED BIMORPH DEVICE



Sarita Thakoor-5
Jan. 1995

CONCLUSION

- FLEXIBLE MICROACTUATORS OFFER A COMBINATION OF HIGH FORCE AND DISPLACEMENT WITH POTENTIAL OF OPERABILITY OVER A WIDE TEMPERATURE RANGE AND A CONTACT-LESS OPTICAL ACTIVATION

- PIEZOCERAMIC BASED FLEXIBLE MICROACTUATORS FORM AN ENABLING TECHNOLOGY FOR A VARIETY OF APPLICATIONS:
  - ADVANCED MOBILITY
  - SHAPE CONTROL
  - MICROVALVES
  - MINIMALLY INVASIVE PRECISION MEDICAL TREATMENT/DIAGNOSTICS

JPL

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  - CENTER FOR SPACE MICROELECTRONICS

JPL

COLLABORATORS

- PENN STATE
  - KENJI UCHINO
  - ERIC CROSS
  - QIMING ZHANG
- CLEMSON
  - GENE HAERTLING
- UNIV. SOUTHERN CALIFORNIA MEDICAL CENTRE
- JET PROCESS CORPORATION

FLEXIBLE MICRO-ACTUATORS

PROPOSAL SUMMARY DRAFT*
Submitted to

Dr. Robert Crowe,
Program Manager,
DSO, DARPA

By

Team members:

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Kenji Uchino, Susan Trolier-Mckinstry: *Penn State University*
Robert J. Full: *University of California, Berkeley*
Takashi Tamagawa: *Jet Process Corporation(Small Business)*
Joe Ye: *VARITY Kelsey Hayes (Large Business)*

*This proposal summary draft from Jet Propulsion laboratory is intended to stimulate discussion of the t epic described. It is not a commitment to work, but is a precursor to a formal proposal if it generates sufficient mutual interest.

EXECUTIVE SUMMARY

Title: **FLEXIBLE MICRO-ACTUATORS**

Principal Investigator: Sarita Thakoor, ***Jet Propulsion Laboratory***
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The overall objective of the proposed effort by a team of researchers from Jet Propulsion Laboratory (JPL), Penn State University, Universit y of California, Berkeley, Jet Process Corporation (small business) and VARITY Kelsey Hayes (large business); led by JPL, is to develop a *flexible* microactuator based on tailored films of lead lanthanum zirconate titanate, PLZT (deposited on flexible substrates) and to demonstrate a multifold enhancement in its force/displacem ent capabilities, compared to those of the current state-of-the-art actuators based on bulk ceramic materials. The effort will be especially aimed at realization and demonstration of the promise of high efficiency actuation of an optimized thin film based bimorph structure by *contact-less optical* ***activation*** in addition to the conventional electrical actuation mechanisms,

Flexible microactuators are envisioned by depositing tailored thick (- 2-10 micron) films of active materials on judiciously chosen, strong flexible (polymeric) substrates. Such flexible microactuators would enable a new generation of non-silicon based micro-electro-mechanical and micro-opto-mechanical systems where the actuation will not be restricted by the clamping effect due to the rigid substrate as in the current silicon based micromachined structures. Also in the current micromachined structures, the actuation force out of the structure is limited by the thickness to which the micromachined structures could be grown, Deposition of tailored piezoceramic thick films by high rate deposition processes, will lead to mobile elements with Substantiality higher force to input power ratio. The key technical challenge is to obtain a tailored PLZT film well adhered to a suitable flexible substrate. This will be addressed by a three pronged approach: (a) development of a process to deposit piezoceramic thin films on high temperature polymeric substrates (such as polybenzo-oxazole), (b) lowering of crystallization temperature of PLZT and/or, (c) delaminating films from high temperature substrates for their subsequent 'lamination' onto flexible substrates such as mylar/kapton. Furthermore, optimization of the material with respect to its defect density, absorption coefficient, optical quality, spontaneous polarization direction, and birnorph geometry could lead to a substantial (up to two orders of magnitude) enhancement in the photoactuation efficiency and thereby allow exploitation of the full potential of the optical actuation effect for photonic control of mechanical motion. Such a flexible, optically triggered microactuator would eliminate the need for an on-board electrical energy source, and open up numerous possibilities of small, light-weight, deployable, optically triggered, contactless actuators, and even solar power driven advanced mobility. Proof-of-concept demonstration of flexible actuators in year 1 and demonstration of the potential of the selected DARPA application in year 2 is the focus of this proposal.

Flexible microactuators constitute an enabling technology for insect-explorers (a new class of small vehicles with advanced mobility emulating the small and agile characteristics of insect mobility combined with dedicated sensing ability). Due to their promise for exploration of difficult, hard-to-reach-terrain, insect-explorers will be ideal for a variety of applications in law enforcement, inspection of hazardous environment, search and rescue in disaster areas such as earthquake sites etc. Additionally such flexible microactuators will be useful for high precision surgery, micropositioning, solar tracking actuator/shutter, direct corrective control in adaptive optics/interferometry, and photophones.

FLEXIBLE MICRO-ACTUATORS

PROPOSAL DRAFT*
Submitted to

Dr. Robert Crowe,
Program Manager,
DSO, DARPA

By

Team members:

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FLEXIBLE MICRO-ACTUATORS

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Robert J. Full: *University of California, Berkeley*
Takashi Tamagawa: *Jet Process Corporation (Small Business)*
Joe Ye: *VARITY Kelsey Hayes (Large Business)*

I. *INTRODUCTION:*

1.1 Need for flexible microactuation:

The emerging field of micro-electro-mechanical systems (MEMS) and micro-opto-mechanical systems (MOMS) holds a promise of revolutionary developments for DoD applications ranging from autonomous mobility platforms (micro-Unmanned Aerial Vehicles), medical diagnostic tools to petaflop computing. On the other hand, NASA's vision of future microspacecraft entails reduction in size of all spacecraft components by orders of magnitude. A breakthrough in actuation technology is required to obtain such size reduction for the next generation DoD and NASA micromobility applications. In the commercial application area, there is an urgent need to miniaturize the size of end-effecters on the medical diagnostic tools such as micro-catheters or endoscopic manipulators, to enable minimally invasive surgery without compromising the mobility and flexibility.

1.2 Advanced Mobility:

in-situ, autonomous exploration and intelligence gathering from surfaces, subsurfaces, and environments for a variety of application scenarios will benefit from a totally new class of exploring vehicles: small in size, mobile and agile like insects, equipped with dedicated microsensors. Large numbers of such inexpensive, and therefore dispensable, explorers would supplement the functions performed by traditional exploration modes. Furthermore, their dedicated sensing functions and small size would be invaluable in hazardous or difficult-to-reach territories for scouting missions. One approach for realization of such vehicles is evolutionary: through the miniaturization of existing wheeled vehicles, Another approach which might offer significant advantages, especially when traversing unusual and difficult terrain such as loose granular surfaces, is to imitate the mobility attributes of insects, Mimicking biology, such artificial insects may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration. They would combine the functions of advanced mobility and sensing with a choice of electronic and/or photonic control. Preprogrammed for a specific function, they could serve as "no-uplink, one-way communicant ing" beacons, spread over the exploration site, *looking for the object of interest.*

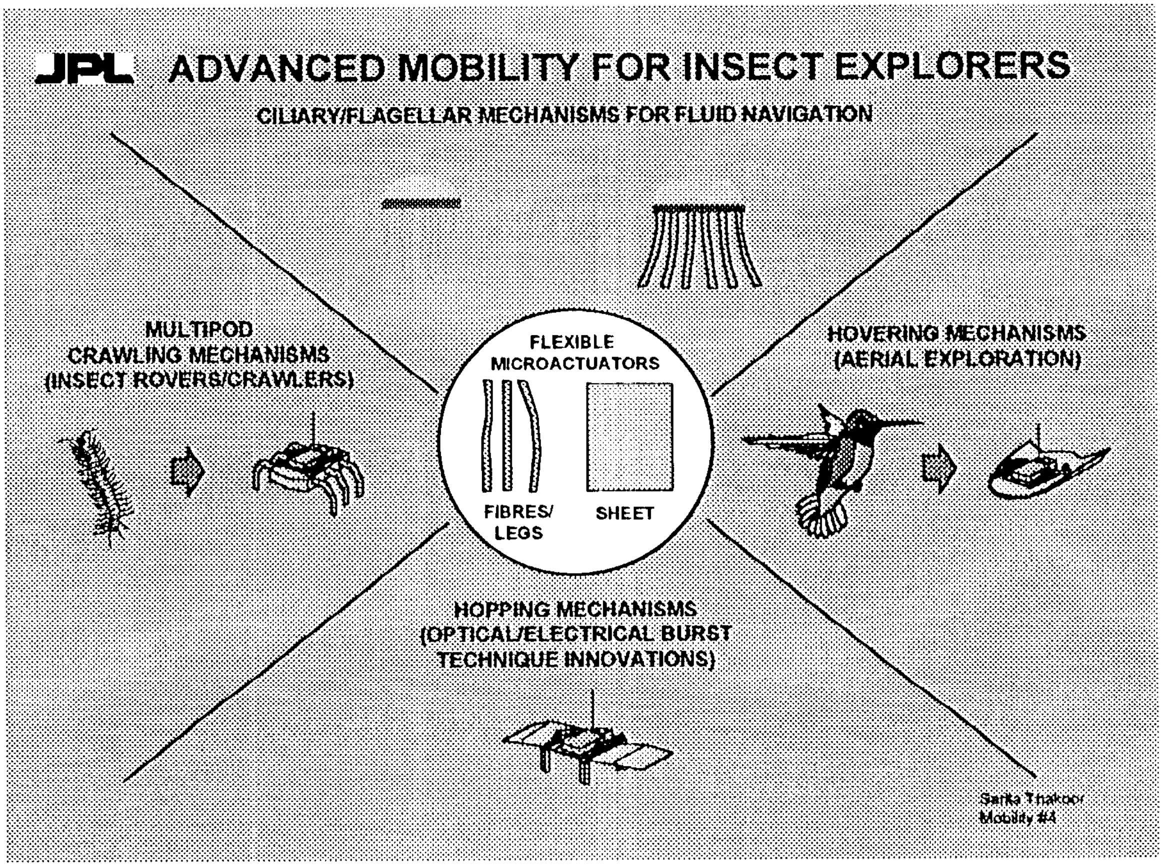


Figure 1

A breakthrough in actuation technology is required to realize the variety of advanced mobility mechanisms for such "insect explorers". ***Flexible microactuators must provide a high force and displacement combination with low power consumption, and must work over wide temperature ranges.*** Figure 1 illustrates four different kinds of insect explorers/in-situ explorers emulating biological mechanisms:

A. Multipod crawlers for surface explorations maneuvering through soft soil and difficult terrain, adaptive to the environment.

B. Ciliary / Flagellar Explorers for navigation through fluids (for e.g. under water exploration for Naval applications)

C. Hopping explorers for surface and aerial exploration

D. Hovering Explorers for aerial exploration

Flexible microactuators that could be addressed/controlled optically and/or electrically would be an enabling technology for insect-explorers. In turn, due to their promise for exploration of difficult, hard-to-reach-terrain, insect-explorers will be ideal for a variety of applications in law enforcement, inspection of hazardous environment, search and rescue in disaster areas such as earthquake sites. Additionally such flexible manipulation could also be used for high precision surgery, optical micropositioning, solar tracking actuator/shutter, direct corrective control in adaptive optics/interferometry, and photophones.

2. *OBJECTIVES:*

The overall objective of the proposed effort is to develop a *flexible* microactuator based on tailored films of lead lanthanum zirconate titanate, PLZT (deposited on flexible substrates) and to demonstrate a multifold enhancement in its force/displacement capabilities, compared to those of the current state-of-the-art actuators based on bulk ceramic materials. The effort will be especially aimed at realization and demonstration of the promise of high efficiency actuation of an optimized thin film based bimorph structure by *contact-less optical* ***activation*** in addition to the conventional electrical actuation mechanisms.

3. *BACKGROUND - EXISTING ART*

Polymeric actuators[2] based on polyvinylidene difluoride (PVDF) and polymethyl-methacrylate (PMMA), although proven for tactile sensing and some high strain applications, have been used with limited success for mobility applications due to their limited force capacity and restricted temperature range of operation and therefore limited cyclability. Some recent[3,4] work on isodactic PMMA has reported high displacements, however the exact nature of the observed effect (coulombic or electrostrictive) is a matter of continuing research. In any case, its potential for providing high strain/force combination and useful work over a wide temperature range is unclear. Ionic conducting polymer gel films (ICPF) discovered by Oguro et al[5] in 1992 have received substantial attention to-date[6,7]. However, the response speed of these actuators is rather slow (several seconds), the drive current is high, temperature range of operation is limited, and they work only in aqueous medium. There is a need for flexible microactuators that could provide a high strain and force combination for low power consumption, and could operate over a wide temperature range for the variety of advanced mobility applications identified above.

4. *PIEZOCERAMIC FLEXIBLE MICROACTUATORS:*

4.1 Why piezoceramic films/microactuators:

Table 1 presents a comparison of the different actuation technologies and illustrates why piezoceramics are the leading candidate, especially when dimensions shrink and approach those of thin films, where properties are generally tailorable by fine composition control, Thin film growth techniques through their close control on composition allow a much finer control of hysteresis and aging properties. In particular, the lower holding power requirement by piezoceramics makes them attractive over magnetic actuators which suffer from the need for significant heat dissipation, With size reduction, the energy absorbed by piezoceramics could be upto two orders of magnitude higher[8] compared to electrostatic and magnetic actuators (Figure 2). This higher density is attributed to the higher dielectric constant of the piezoceramics and the increasing breakdown field with reducing thickness[8]. Furthermore, piezoceramics offer the potential of solar driven, tetherless mechanisms since they can be actuated[9,11] directly by optical illumination (350nm to 450 rim). Piezoceramic actuation is potentially robust, amenable to low temperature (deep space) operation, and intrinsically radiation-resistant. In addition, their ability to be batch-produced by thin film manufacturing techniques on large substrate areas offers convenience and cost effectiveness.

WHY PIEZOCERAMIC ACTUATION?

(AS WE SCALE DOWN TO THIN FILM PIEZOCERAMICS)

			POLYMERIC MATERIALS		
	PIEZOCERAMIC	SHAPE MEMORY ALLOY	PVDF	Polymides PMMA Polyurethanes	MAGNETO-STRICTIVE
MECHANISM	PIEZOELECTRIC & ELECTROSTRICTIVE	THERMAL MARTENSITIC-AUSTENITIC PHASE CHANGE	PIEZOELECTRIC, PHASE TRANSITION	ELECTRO-STRICTIVE	MAGNETIC FIELD INDUCED BY COIL
STRAIN	10^{-7} TO 0.3×10^{-2}**	10^{-4} TO 10^{-1}	10^{-4} TO 10^{-1}	10^{-6} TO 10^{-2}	10^{-4} TO 10^{-2}
DISPLACEMENT	LOW TO HIGH*	MEDIUM TO HIGH***	LOW TO HIGH	LOW TO MEDIUM	MEDIUM
FORCE	HIGH ~100 kgm FORCE	LOW-MEDIUM ~1 kgm FORCE	SMALL	sMALL	HIGH
HYSTERISIS	TAILORABLE BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	LARGE
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	-196°C -> 300°C WIDE	-196°C -> 100°C WIDE	-10°C -> 60°C LIMITED	-10°C -> 80°C LIMITED	-273°C -> 100°C WIDE
RESPONSE SPEED	μsec-msec	seconds	msec	msec	μsec-msec
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	LOW	LOW	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	YES	TBD	TBD	TBD	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR-POOR	GOOD
PROSPECT OF MINIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAIR

PIEZOELECTRICS REPRESENT A LEADING CANDIDATE FOR ADVANCED MICROACTUATION

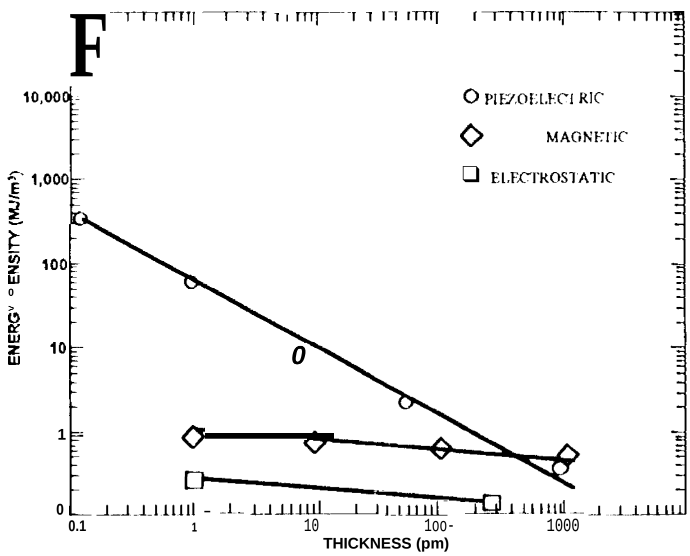
* With amplification techniques (e. 9. optically or electrically activated bimorph, flextensional elements and combination thereof to obtain double amplification)

" Antiferroelectric phase transition materials

*** Limited by Thermal Energy Input

Table 1

power consumption (extremely low holding current), the 2 micron film microactuator is extreme] y attractive to implement.



Energy density as a function of film thickness

Figure 2

4.3 Optically Activated Actuation:

Two oppositely poled lead lanthanum zirconate titanate (PLZT), ceramic wafers bonded together to form a piezoceramic bimorph (as shown in fig 4a) exhibit a large photodeflection, analogous to a piezoelectric bimorph. Essentially the differential strain in the two oppositely poled wafers gives rise to a large deflection of the bimorph element A deflection as high as -200 micron, away from the direction of the light, has been obtained from a bimorph -2 cm long, -0.5 cm wide, and ~0.4 mm thick, when exposed to an intensity of- 80mW/cm^2. In such a deflection, a force of ~10 gm is generated at the tip of the bimorph. In fact, PLZT ceramic wafers have been earlier used[13,14] to demonstrate two different kinds of mobile walking and gripping devices based on such photoactuation in ceramics. However the limited photonic energy to mechanical conversion efficiency (- O. 10/0) obtained in the ceramic due to its poor optical quality left those demonstrations as mere curious experiments. ***With the recent emergence of thin film growth techniques for piezoceramic PLZT films, a new opportunity has arisen in exploiting the full potential of this optical actuation effect for photonic control of mechanical motion.*** As detailed in the next section, optimization of the material with respect to its defect density, absorption coefficient, spontaneous polarization direction, and bimorph geometry (aspect ratio, etc.) could lead to a substantial (up to two orders of magnitude) enhancement in the photoactuation efficiency. A flexible PLZT film microactuator thus enhanced, clearly would bypass the need for an electrical energy source, and open up numerous possibilities of deployable, optically triggered, contactless actuators, and even solar power driven advanced mobility.

Clearly, such ***advanced mobility*** *(ciliary/flagellar mechanisms, multipod inchworm/crawling mechanisms)* would be tetherless, and either autonomous or remote-controlled, The prohibitive weight and mobility restrictions due to an umbilical power cord would be eliminated. The photogenerated deflection could be used to directly "walk" on the surface or to run motors for indirect locomotion. Such tether-less optical control of advanced mobile vehicles would also be desirable for exploration of hazardous, hard to reach locations, as long as at least a line of sight exists. Piezoceramic bimorphs provide a good trade of load versus displacement for piezoceramics and have been used for a variety of applications. Optically driven bimorphs have a similar niche for applications requiring high displacement and low load requirement with the added versatility of photonic addressing.

5. *SIGNIFICANCE AND INNOVATION*:

Flexible microactuators are envisioned by depositing tailored thick (- 2-10 micron) films of active materials on judiciously chosen, strong flexible (polymeric) substrates. **Flexible microactuators would provide a combination of high force and displacement and be operable over a wide temperature range as is required for a variety of advanced mobility applications.** Potential advantages of flexible microactuators are:

- low power (low voltage operation, <5 V), low mass, low volume
- high force/volume even with low voltage operation
  higher deflection
- flexible, miniaturizable microactuator: scaleable for MEMS/MOMS
  excellent cyclability -more than million cycles
  amenable to both electrical or optical activation

Schematically fig 6b (on page 15) illustrates **such a** flexible actuator. It can be formed in the form of fibers or sheets (figure 1) as demanded by the application.

The significance of the proposed work is two fold. First, the high energy density offered by piezoceramic thin films, allows up to five times enhanced ratio of output force per unit volume for a film bimorph with operation at the Si-VLSI compatible low voltage of 5 V. Second, is the promise of upto two orders of magnitude enhanced photons to mechanical conversion efficiency in a piezoceramic flexible bimorph when activated optically accompanied with upto two hundred times higher ratio of output force to input power. Specifically optical control has following advantages:

- contactless control/remote control
- low power solution
- electrode-less, contact less structure
- enhanced reliability, external voltage not required (breakdown issues avoided)
- microdisplacement proportional and controllable by the intensit y of the light energy

Such flexible microactuators would enable a new generation of non-silicon based microelectro- mechanical and micro-opto-mechanical systems where the actuation will not be restricted by the clamping effect due to the rigid substrate as in the current silicon based micromachined structures. Also in the current micromachined structures, the actuation force out of the structure is limited by the thickness to which the micromachined structures could be grown. Deposition of tailored piezoceramic thin films on flexible substrates would substantially eliminate the substrate clamping effect and thicker films can be deposited by high rate deposition processes, leading to mobile elements with substantially higher force to input power ratio.

6. *APPROACH:*

The technical approach to develop and demonstrate flexible microactuators therefore will aim at the overall optimization/maximization of the extent of deflection combined with a low power, high force capability using electrode less optical activation. This will be done within the following five distinct work-items that sequentially depend on each other:

6.1 Optimization of Photoactuation in Ceramic Bimorph Structures: This subtask will combine Penn State's unique capability to tailor-make ceramics with optimum doping for the photoactuation effect and JPL's unique expertise in high speed photoresponse investigations, thin film device design and applications. It is known that the optical actuation effect (extent of the photodeflection) is a direct but complex function of (1) material microstructure, crystalline orientation, and the actual geometry (configuration/ structure/ dimensions, etc.) of the bimorph; and (2) the intensity, and angle of incidence of the light illumination, triggering the effect. This subt ask will consist of the following sub-work items:

a. Optimization of the Effect: Establish a quantitative interdependence (and cross correlation's) among the piezo properties, photodeflection, and material characteristics (micro-structure, crystal orientation, etc.) by systematically studying the behavior of the materials with respect to:

thickness of the ceramic wafer to verify the '(penetration depth" hypothesis,
composition variation and selected dopants to tune the wavelength response,
variation of orientation of polarization axis, and
variation of surface roughness of samples to examine the absorption dependence.

b. Feasibility Demonstration: Determine the exact coupling factors between the illumination (intensity, angle of incidence, plane of polarization etc and the photodeflection for selected sample geometries. A thorough and systematic study of photodeflection under various illumination conditions will not only lead to a feasibility demonstration of the concept but will also establish the 'outer bounds' of the phenomenon.

c. Extension to Visible Wavelengths: The photocurrent generated in the ceramic is strongly dependent on the wavelength under a constant intensity of illumination as reported[10] earlier by Uchino et al. Suitable donor doping can shift[10] the peak response from 372 nm in $PbLa_{0.03}Zr_{0.52}Ti_{0.48}O_3$ to 384 nm in $0.9[PbTiO_3]$- 0.1 $[La(Zn_{0.67}Nb_{0.33})O_3]$. This peak occurs near the absorption edge of the corresponding ceramic composite material. Therefore, an attempt will be made to extend the response towards the blue color region generating less deep donor -type impurity levels. The suitable candidate dopants include Mg, Ni, Co, and Cu. Also donor doping with (Nb, Ta, W) with less than 1 atm% on the B site has been observed[11] to enhance the photovoltage response without compromising on the piezoelectric effect. For a solar powered mobile device this will have the effect of increasing the efficiency by 3 0°/0 to 50% because the solar irradiance is maximum[24] at blue wavelengths. Thus by proper selection of dopants and optimization of ceramics to respond to visible wavelengths of the solar spectrum the photoactuation effect could be extended to a wider range of applications. Ceramic compounds such as $PbTiO_3$ - Pb(A . WY) O_3 where A =- Mg, Ni, Co, Cu will be investigated, The samples will be prepared by the conventional mixed-oxide method described elsewhere[9-11].

d. Separation of Pyroelectric and Photostrictive Effect: Preliminary observation of the photoactuation effect on typical ceramic bimorphs has indicated that consequent to light illumination at 360 nm, there is a fast response - milliseconds giving rise to - 20 microns of photodeflection followed by a slow increase in deflection possibly thermal in origin which leads to -200 micron total deflection in a matter of few seconds. The approach would be to differentiate between the two effects: electronic/electro-optic and thermal, and understand them better in order to exploit the potential of the former to obtain a fast response micromobility application.

6.2 **Fabrication of Flexible Microactuator Structure:** Flexible microactuator test structures would be fabricated by depositing tailored thin (2-1 O micron thick) films of selected composite piezoceramic material (e.g. PLZT) films on suitably selected flexible film substrates. The key technical challenge is to obtain a tailored PLZT film well adhered to a suitable flexible substrate. This will be addressed by a three pronged approach: (a) development of a process to deposit piezoceramic thin films on high temperature polymeric substrates (such as polybenzo-oxazole) (b) lowering of crystallization temperature of PLZT and (c) delaminating films from high temperature substrates for their subsequent 'lamination' onto flexible substrates such as mylar/kapton:

a. High Temperature Polymeric Substrates:

To deposit the piezoceramic film directly onto a flexible substrate, the substrate must have high temperature stability, high strength (Young's Modulus - 4.9×10^{10} N/m2), a close match of thermal coefficients of expansion with the piezoceramic film, and a tailorable crystal orientation in order to provide a desired template for growth of oriented PLZT. Earlier work has shown[16] that ferroelectric quality PZT could be crystallized at - 550°C. Recently[17] polybenzoxazole (PBO) has been validated at JPL to work well up to ~550°C and extensively characterized for operation at 460°C. Table 2 & 3 provide a comparison of a variety of substrate films and fibers. PBO stands out as the leading candidate for its high tensile strength, high Young's Modulus, low heat shrinkage and coefficients of thermal expansion and hydroscopic expansion to provide such a high temperature substrate for forming flexible microactuators by this technique. PRO is a conjugated aromatic hetrocyclic liquid crystalline polymer (LCP) with a chemical structure as shown in Figure 3.

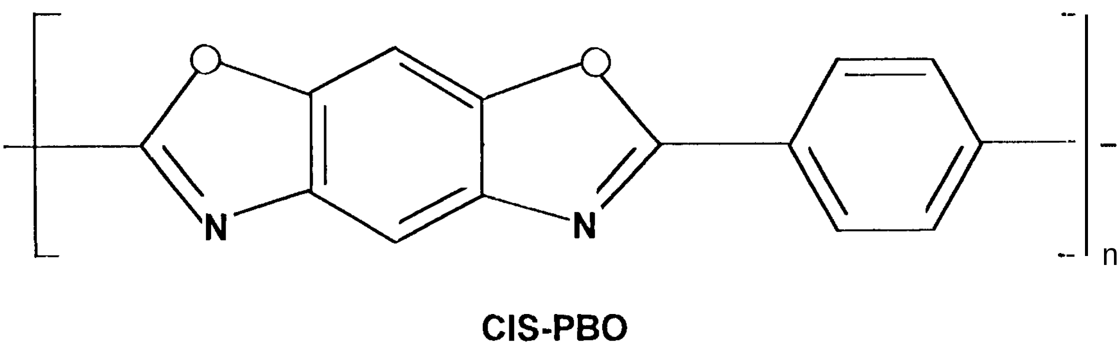


Figure 3. Chemical Structure of PBO

PROPERTY	UNIT	KAPTON	ARAMID	PET	PEN	PBO
DENSITY	g/cm^3	1,420	1,500	1,395	1.355	1.54
MELTING TEMP	'c	NONE	NONE	263	272	NONE
GLASS TRANSITION TEMP	°C	350	280	68	113	NONE
YOUNG'S MODULUS	kg/mm^2	300	1000-2000	500-850	650-1400	4900
TENSILE STRENGTH	kg/mm^2	18	50	25	30	56-63
TENSILE ELONGATION	o/o	70	60	150	95	1-2
LONG-TERM HEAT STABILITY	"c	230	180	120	155	>300
HEAT SHRINKAGE (200°C x % rein)	%0	0.1	0 . 1	5-1o	1.5	<0.1
COEFFICIENT OF THERMAL EXPANSION	ppm/°C	20	15	15	13	-2
COEFFICIENT OF HYDROSCOPIC EXPANSION	ppm/% RH	20	18	10	10	0.8
MOISTURE Absorption	0/0	2.9	1.5	0.4	0.4	0.8

Table 2: comparison of a variety of polymeric films

The chemical synthesis of PBO results in a LCP solution that is processed to fiber or film by various techniques. The high strength and superior physical properties of PBO are due to the rod-like nature of the PBO molecule (Figure 3) and the orientation that can be built into the Polymer film. P130 film's self-reinforcing microstructure results in a "molecular fabric" with properties comparable to those of advanced, fiber-reinforced materials, but without the drawbacks of distinct fiber and matrix components. This polymer has no melting point or glass transition temperature.

PROPERTY	PBO	PBO HIGH MODULUS	ARAMID	STEEL	SPECTRA® (HDPE)	CARBON (HI-TENSILE)	GLAS (s-2)
TENSILE STRENGTH (ksi)	820	800	400-500	250	435	500-700	665
TENSILE MODULUS (Msi)	25-30	40-45	10-25	29	25	30-40	12.6
COMPRESSIVE STRENGTH (ksi)	40	65	65	250	10	300-400	>150
ELONGATION, BREAK (%)	3.0	1.5	1.54.0	2.0	3,5	1.5-2.0	5.4
DENSITY (g/cc)	1.56	1.56	1.44	7.86	0.97	1.8-1.9	2.4
SPECIFIC TENSILE STRENGTH (ksi)	525	510	280-350	32	450	270-380	280
SPECIFIC TENSILE MODULUS	16	26	7-18	4	26	16-22	5
LIMITING OXYGEN INDEX (LOI: %)	56	56	30		19	50-65	

Table 3: Comparative data for high performance fibers

b. crystallization of PLZT at Lower Temperatures:

Rapid thermal annealing (RTA) using localized laser annealing to obtain crystallization of the desired piezoactive phase of PZT/PLZT at temperatures even lower than 550 C will be investigated. This will further reduce the constraints on the requirements of the flexible substrate and widen the choice for selection of flexible substrates.

c. lamination onto Selected Flexible Substrates:

i. Bonding of films, previously delaminated from elsewhere: Piezoceramic films deposited on the known high temperature substrates (e.g. alumina or silicon) would be delaminated after crystallization by controlling the adhesion of the film onto the substrate. The delaminated piezoceramic film would then be mounted/bonded onto the selected flexible substrates.

ii. Thinned Si/SiN Substrates: Another approach to be performed in collaboration with Dr. Susan Trolier Mckinstry at Penn State is to deposit the piezoceramic thin film on thinned Si/SiN wafers and then bond these structures onto the flexible substrates. During phase 1 the feasibility of using micromachined diaphragm and cantilever structures as mechanical amplifiers for thin film-based actuators in flexible structures will be determined, The approach taken here will be to fabricate the piezoelectric thin films on platinum-coated silicon substrates, micromachine them to achieve mechanically-amplified displacements, and dice out individual elements for incorporation onto the flexible substrate(with no special requirements for high temperature capability). This enables the piezoelectric film to be processed under conditions in which large piezoelectric coefficients have already been demonstrated (d_{33} = 70-220 pm/V, $-d_{31}$ = 80 - 100 pm/V in undoped PZT). It also eliminates problems associated with firing a polymeric substrate material at high temperatures (>550oC in an oxidizing ambient).

An assessment of the most promising of the above three approaches will be made in phase 1 and the most promising approach pursued in Phase 2.

6.3 **Optimization of the Piezoceramic films by Multi-Magnetron Sputtering:** The technique[16] (earlier patented by Sarita Thakoor) of multiple-sequential-target sputter-deposition, compatible with low temperature microelectronic processing, holds promise for deposition of films with tailored composition and will be extended for deposition of the multicomponent oxide piezoceramic films of lead lanthanum zirconate titanate (PLZT). This technique by providing better mixing of the components and closer control over the solid state chemical reactions during post-deposition annealing, as each individual metal layer in the deposited multicomponent stack could be effectively extremely thin (even a fract ion of a monolayer) provides enhanced control over the composition of the deposited film. The parameters from this multi-magnetron process can be easily extended to the JVD process for high rate piezoceramic film deposition patented by Jet Process Corporation and therefore this collaboration will allow an easy transition of the experimental process to manufacturing of flexible microactuator structures by JPC 's manufacturing process.

The film quality improvement will be achieved by combining the following:

(a) Optical quality enhancement: The defect density in a thin film could be lowered by over an order[18,19] of magnitude, thus reducing scattering losses that are common in the ceramic wafer. Figure 4 shows a comparison of the scanning electron micrograph pictures of ceramic (figure 4a) and optical quality (figure 4b) layers, Also the optical absorption coefficient in a thin film could be tailored to be almost 20 % higher than that in the bulk materials. **An order of magnitude better absorption is expected in the thin film compared to the ceramic wafer leading to a correspondingly higher efficiency**.

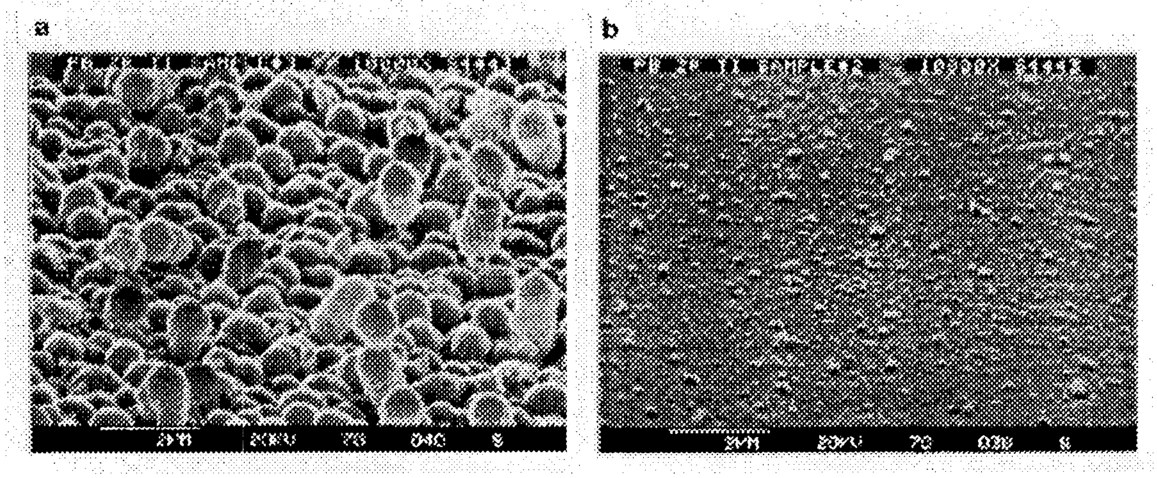


Figure 4: **A comparison of the scanning electron** micrographs **of ceramic** (figure 4a) and optical quality (figure 4b) PLZT layers.

(b) Polarization Direction and Intensity optimization: Photoresponse from ferroelectric thin films of lead zirconate titanate (PZT) is shown[20,21] to be maximum when the electric field vector associated with the incident light is parallel to the c axis in the material.

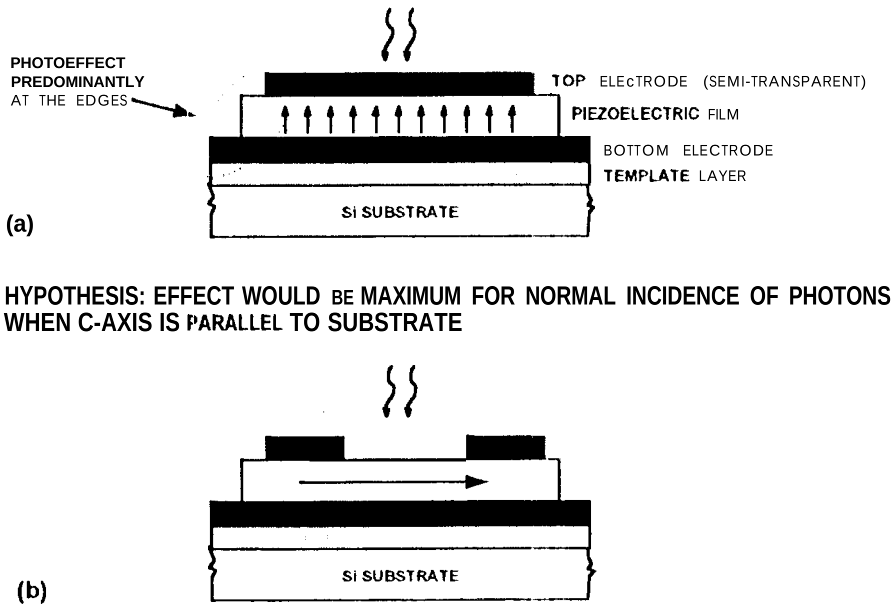
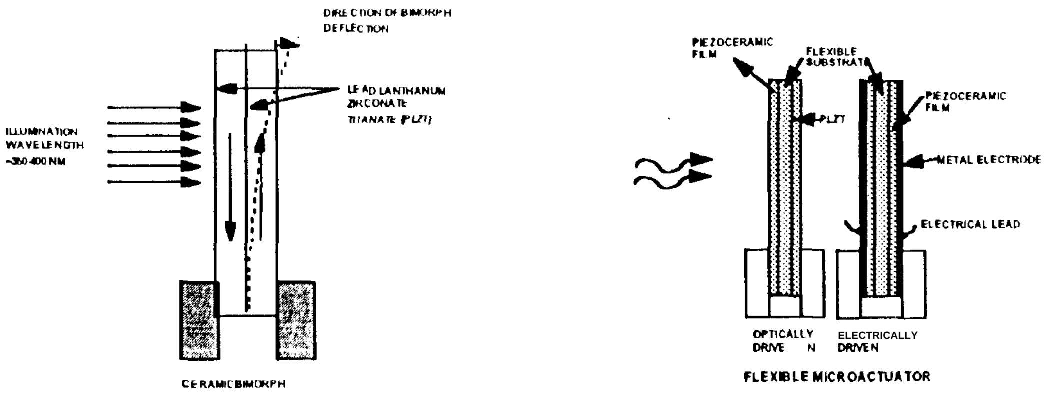


Figure 5: (a) PZT Thin film Capacitor where PZT has its c-axis oriented perpendicular to the substrate, (b) Conceptual design of a PZT capacitor with c-axis parallel to the substrate which is expected to maximize the photoeffect.

In fact, the observed small effect from the edges of the ferro-capacitors as shown in figure 5a (with c axis predominantly perpendicular to the substrate) was primarily attributed to the domains which had some angular variation (estimated to be in the range of+/- 10 to 15 degrees) with respect to the substrate perpendicular. Such photoeffects are known[22] to exhibit enhancement by over an order of magnitude when the alignment of the incident E field with the c axis changes from nominally 10 degrees to - fully parallel. Piezoceramic PLZT is also ferroelectric and therefore the photodeflection effect is expected to be maximum when the photonic electric field is parallel to the spontaneous polarization in the ceramic (namely, the c axis,), optimization of the angle of incidence and tailoring the direction of spontaneous polarization in the ferroelectric will lead to maximum interaction with photon incidence and thereby maximum photodeflection. **This optimization (shown in figure 5b)** will allow **design of a bimorph with another order of magnitude enhancement in efficiency**.

(c) **Optimization of the Optical Penetration** Effect: Since the absorption of the illumination occurs in at the most 1 to 1 O micron skin of the piezoelectric material facing the illumination, the photovoltage generation is expected[23] to be entirely located in this thin top skin layer. Using a film thickness equal to this penetration depth ensures that the entire film is active. In a ceramic typically ~ 200 micron thick, almost 95 % of the bulk is an inactive mass to be moved. in films, therefore significantly larger displacements are expected.



ceramic thickness: 200 micron　　　　film thickness: 2 micron

(a)　　　　**(b)**

Figure 6

Figure 6a and figure 6b compare a ceramic bimorph and a flexible film bimorph. The table 4 below shows the projected parameters of improvement. The numbers in this table are evaluated based on using a 200 micron thick typical ceramic wafer as the current state of the art and a 2 micron thick film as the projected flexible film bimorph. Such a film bimorph activated with 5 V will have ~ 25 times higher energy density than the ceramic bimorph that requires -100 V. In turn, although the net force output from the bimorph will be 20 % of that from the ceramic, the force /volume will be five times higher. Correspondingly, in the case of optical actuation, the film bimorph is projected to deliver force output 2-20 times that of the ceramic due to the enhancement in conversion efficiency (expected value - (10/0 -10%). This will result in an enhancement of force per unit power by 20 to 200 times. Obtaining the optical performance enhancement in input photonic power to output mechanical force will as indicated provide a substantially enhanced bimorph. Demonstration of this matrix of improvement will set the foundation of photonic control of mechanical motion.

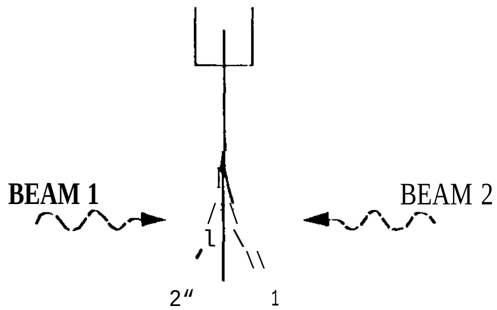
6.4 **Optical Activation** Study: The exact relationship between the photovoltage, photodeflection, and the illumination intensity will be established to identify the deflection saturation point and limits of the design parameters for a mobility application. The illumination sources to be used for these photoresponse measurements include a 355 nm, compact Nd-Yag laser and a short arc (300-600nm) mercury lamp, with a spectral line filter allowing illumination at 360nm. Guided by the results of the work items 6.1 and 6.3 on optically actuated structures, thin film photostrictive materials will be prepared by the selected techniques that provide the compositional fidelity required to permit rapid prototyping of the optimized compositions of PLZT to form flexible microactuators. The amplitude and the speed of the photostrictive response will then be examined on the film bimorph versions that will be fabricated using the selected approach of 6.2. Clearly, optimization of the flexible film microactuators will be dictated by the results of the bulk ceramic optimization (as described in Section 6.1).

		Current Status Ceramic Bimorph	Projected improvement Film Bimorph
ELECTRICAL ACTIIATION PARAMETERS	**Thickness**	**200 microns**	**2 microns: Thickness reduced, material tailored**
	Operating Voltage	**100 v**	**5 V : Operational voltage reduced**
	Energy Density	**1 X**	**2S X : Inherent advantage of reduced thickness**
	Force/Energy	**5F**	**F**
	Force/Volume	**1X**	**5X enhancement for film bimorph**
OPTICAL ACT[IATION PARAMETERS	**Optical Power**	**80 mW/cm^2**	**8 mW/ cm^2 : Illumination Intensity reduced by 10 times**
	Power Ratio	**1 0X**	**1X**
	Photonic to Mechanical Energy Conversion Efficiency	**0.1 %**	**1 %- 10 % : significant enhancement in overall efficiency**
	Force /Energy	**F**	**2F to 20F : Multifold enhancement in the film bimorph**
	Force /Power	**1X**	*20X* **to** 200X

TABLE 4: Flexible film microactuators, matrix of improvement

6.5 Demonstration of Advanced Microactuation of a Film Bimorph: In this subtask, the enhanced microactuation triggered by both electrical as well as optical activation will be demonstrated on a thin film bimorph structure (Fig 6. b), One of the applications highlighted in Section 1 will be selected for demonstration as a proof of concept. For example, application of

BASIC PRINCIPLE ALTERNATING DEFLECTION OF INDIVIDUAL BIMORPH DEVICE



ALTERNATING PHOTODEFLECTION OF THE BIMORPH WHEN ILLUMINATED WITH ALTERNATING LIGHT PULSES FROM THE TWO SIDES

CRAWLER TYPE TRANSLATIONAL MOTION OF TWO LEGGED BIMORPH DEVICE

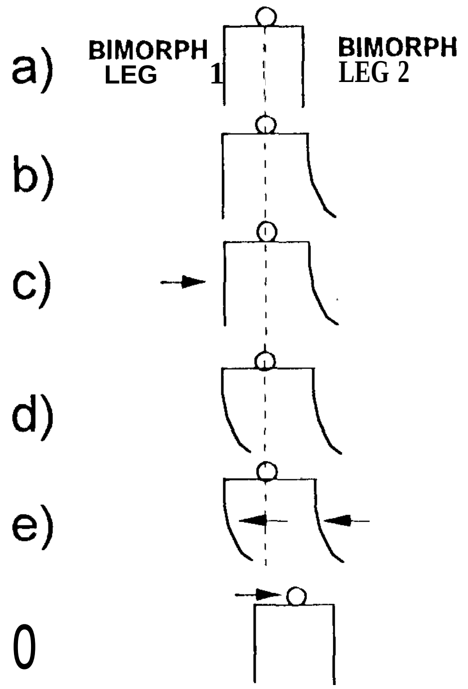


Figure 7

an alternating voltage would generate a vibratory motion in the bimorph. On the other hand, vibratory motion of the bimorph could be optically triggered by using a two beam arrangement to alternately illuminate the two sides. Quantitative measurement of the deflection will be done using the optical spot deflection technique and a Polytec Inc (P]) Laser Vibrometer. The laser vibrometer utilizes a Mach Zehnder interferometer in conjunction with the Doppler shift measurements to evaluate the velocity as well as acceleration of the deflection, thereby allowing determination of force. As an example of mobility, a motion sequence for a two legged crawler is illustrated in figure 7. Initially light is incident on leg # 2 from inside (left) so it moves/bends to the right. Following light incidence on # 1, makes it deflect to the right too. In the next step light is incident on both legs from the right causing both legs to straighten and making the head move to the right. An appropriately sequenced electrical trigger signal could also generate the bimorph leg motion.

7. *TASKS:*

Proof-of-concept demonstration of flexible actuators in year 1 and demonstration of the potential of the selected DARPA application in year 2 is the focus of this proposal.

PHASE 1 (DURATION 1 YEAR):

This proposal gives a detail of the approach for Phase 1 which will specifically be divided into following subtasks:

- **investigation/Optimization of optical actuation in ceramic bimorphs:** This will be done in collaboration with Penn State (Dr Kenji Uchino) on ceramic bimorphs according to the approach detailed in Section 6.1 to determine the outer bounds of the phenomenon of photoactuation and will lead to demonstration of optimized photodeflection in ceramic bimorphs.

- **Fabricate flexible microactuator** test **structures by depositing** single layers of piezoceramic film on selected flexible substrates utilizing the four distinct approaches detailed in Section 6,2 in collaboration with Jet Process Corporation (Takashi Tamagawa) and Penn State (Susan Trolier Mckinstry).

- **Characterize flexible microactuator test structures for their performance** both by electrical and optical activation utilizing measurement techniques at JPL and Penn State.

- **Optimize electrically and optically driven flexible microactuator** for higher deflection and force/power ratio as detailed in Section 6.3 and 6.4.

- **Demonstrate improvement projected for single layer film bimorph in** table 4 using the approach described in Section 6.5.

- **Identification of a DARPA -relevant application scenario** to showcase impact of flexible microactuation .

- **Form firm alliances with industry (Large Business) for follow-on Phase 2 :** Sarita Thakoor is in communication with Lockheed Martin, Rockwell, and VARITY Kelsey-Hayes to obtain their commitment in leading the flexible microactuator development for advanced mobility applications in the following phases. Members at each of these companies have expressed substantial interest in the concept. JPC and VARITY Kelsey Hayes (letters of support attached pp 22, pp 30 respectively) indicated their readiness in providing us infrastructure support in their respective areas.

PHASE 2 (D1JRATION :1 YEAR)

The outline of the second phase is as follows:

. **Design innovative mechanisms for mobility emulating biology** utilizing the data obtained from flexible microactuator test structures in Phase 1 for the applications selected in Phase 1. This activity will be performed at JPI, in collaboration with Dr. Bob Full at UC Berkeley

. **Fabricate flexible microactuators optimized structures.** This will be done in collaboration with JPC (Takashi Tamagawa) and Penn State (Susan Troiler-Mckinstry).

. **integrate flexible microactuators to form mobile elements.** This will be done at JPL in collaboration with the Large Business/es for the selected application.

- **Demonstrate the performance of the flexible mobile element .** This will be done in collaboration with the identified Large Business/es

PHASE 3 (DURATION 2-3 YEARS):

. **Demonstrate prototype of an insect explorer** for the selected DARPA relevant application.

8. *COST ESTIMATE:*

Phase 1 (Year 1): **JPL, 1.6** WY(includes procurement to JPC for depositions and travel costs for consultant at UC Berkeley) : 256 **K**

JPL, 1.6 WY(includes procurement to JPC for depositions and travel costs for consultant at UC Berkeley) :	256 **K**
Penn State (Dr. Kenji Uchino):	**64 K**
Penn State (Dr. Susan Trolier Mckinstry):	**20 K**
Total	**340 K**

Phase 2(Year 1)::	**JPL,** 2.8 WY :	**464 K**
	Penn State :	**144K**
	UC Berkeley :	**72 K**
Total:		**680 K**

in addition, team members JPC and VARITY Kelsey Hayes will contribute their infrastructure support to this development effort (refer pages 22 and **30** respectively)

Phase 3: **TBD**

9. REQUIRED EQUIPMENT AND FACILITIES:

The deflection measurement will be done using the optical spot deflection technique and a Polytec P]., Laser Vibrometer and both equipment are in place in Division 34 and 35 respectively at JPL. The Polytec PI manufactured laser vibrometer together with the auto-tracking optics and a fast data acquisition system designed by NASA LeRC are available. The whole system is compact and portable, allowing on-site measurements in conjunction with several different types of applications. The optical sources required are also available in Div 34 & 35 of JPL. The deposition of piezoceramic films on flexible substrates will be done in collaboration with Jet Process Corporation (letter from JPC attached, page 22). Piezoceramic characterization techniques and measurement techniques existing both at JPL and Penn State will be utilized.

10. RESUMES:

Sarita Thakoor, MS, MPhil in Physics from Univ of Delhi India (1977, 1979), Member of the Technical Staff at JPL will lead this effort. She has been involved at JPL/CALTECH for the last twelve years in the R & D of a variety of novel thin film memory devices for neural net works, non-volatile ferroelectric memories, and microactuators for robotics and active control. Within the last six years, she has taken a lead role in piezoceramics/ferroelectrics and created/conceptualized innovative designs of piezoceramics based devices/applications, in particular flexible microactuators. She holds five patents including three on device designs for ferroelectric memories and electro-optically addressed devices with non-destructive readout. She has published over 18 refereed articles and made 30 conference presentations. She serves as a member of the editorial board of the journal "integrated Ferroelectrics" and a member of IEEE. She is a recipient of over twenty certificates of recognition/awards from NASA for new technology innovations. Her current research interests include ferroelectric and piezoceramics for robotics, micromobility, biologically inspired advanced mobility, microactuators for shape control and biomedical applications, sensors, and non-volatile memories. (further detailed resume pp32-36)

John Michael Morookian received the B.S. degree in Electrical Engineering from the University of Southern California, Los Angeles, California and subsequently assumed a full-time position at the Jet l'repulsion laboratory, California Institute of Technology, Pasadena, California in May 1991. During his four years as an undergraduate at USC, he worked at the Center for Laser Studies, furthering research in optical memory systems, power-by-light applications, and optical Code Division Multiple-Access (CDMA). He has co-authored several papers on these subjects. He came as a summer student in 1990 to JPL's High Speed Optical Systems Group, Section 341, where he designed an autocorrelator for measuring sub-picosecond optical pulses. He has worked at the JPL assisting with the analysis, design, and construction of an optical CDMA scheme, including a femptosecond laser pulse source, optical non-destructive readout of ferroelectric memories and recently set up spot deflection technique for measuring deflection.

Mr., Morookian is a member of the USC Engineering Honors Group, Alpha Lambda Delta, and Tau Beta Pi.

Abhijit Biswas, PhD will be responsible for laser vibrometry. He is currently a member of technical staff with the Microgravity Research Group at Jet Propulsion Laboratory (JPL). He has a Ph.D. awarded by the Molecular Science Program, and a MS degree in Engineering Mechanics & Materials from Southern Illinois University at Carbondale, Illinois. His Bachelor's degree is in Metallurgical Engineering from the Indian institute of Technology. He has over 30 publications and has served as PI and CO-PI for US Army Research Office grants. He was recipient of a National Research Council Associateship. He is an active member of the Optical Society America,

Andre H. Yavrouian MS Organic and Polymer Chemistry, University of Sofia 196S. Analytical Chemistry Group Supervisor whose contributions include evaluation, characterization, qualification, and testing of materials for a variety of applications that include planetary balloons; adhesives for military applications; Wide Field Planetary Camera and various other flight projects; propellants for Mars Observer, Galileo, and TOPEX; hybrid fluorocarbons for use as artificial blood substitutes; Saran Carbon for sorption cryocooling; fuel additives to suppress post-crash aircraft fires; pharmaceuticals and biomedical chemicals. He also has extensive experience in polymer synthesis including acrylic-based polymers for water purification, polyurethane for electronics parts encapsulation, and polymerizable UV absorbers for solar cell encapsulation. He has over fifty patents and technical publications to his credit.

RESUMES of other team members and their respective support letters are attached (pages 22-31)

11. *REFERENCES:*

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3. M. Shahinpoor, G. Wang and M. Mojarrad, "Electrothermo-Mechanics of Spring-Loaded Contractile Fiber Bundles with Applications to Ionic Polymeric Gel and SMA Actuators", Proc. Int. Cong. Intelligent Materials, ICIM'94, edited by C.A. Rogers and G.G. Wallace, Technomic Press, pp. 1105-1116, (1994).
4. M. Shahinpoor and M. Mojarrad, "Active Musculoskeletal Structures Equipped with A Circulatory System and A Network of Ionic Polymeric Gel Muscles,", Pro. ICIM'95, edited by C.A. Rogers and G.G. Wallace, Technomic Press, pp. 1079-1085, (1995).
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16. S. Thakoor, US patent # 5196101, March 23, 1993.
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18. S. Thakoor, and J. Maserjian, "Photoresponse Probe of the space charge distribution in Ferroelectric PZT thin film memory capacitors" J. Vat. Sci. & Tech A, **12**, 295, Mar/April(1994).
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21. S. Thakoor and A. P. Thakoor, "Optically Addressed Ferroelectric Memory with Non-Destructive Readout", Applied Optics, 3136, Vol.34 (199S).
22. Ml-lass, P. A. Franken, and J. F. Ward, Optical Rectification, Phys. Rev. A, 138, 534-542, (1965).
23. Y. Miyazawa, K. Uchino and S. Nomura, Ferroelectrics Letters, 44,341 (1 983).
24 C. Elachi, Introduction to the Physics and Techniques of Remote Sensing (John Wiley & Sons, 1987), p. 47.

Jet Process Corporation
Thin films by the JVD™ process

August 27, 1996

Ms Sarita Thakoor
Jet Propulsion Laboratory
MS 303-308
4800 Oak Grove Drive
Pasadena CA 91109-8099

Dear Santa:

I'd like to express again my appreciation for our recent discussions on concepts for flexible actuators and concepts for advanced mobility using piezoelectric ceramic tin films such as those in the lead lanthanum zirconate titanate (PLZT) family. The idea of fabricating bimorph structures using thin ceramic films on polymeric substrates will have many applications. Jet Process will therefore support your DARPA proposal on flexible microactuators, as it is synergistic with a number of programs already in progress as well as proposed at the company.

Jet Vapor Deposition has the advantage of being a high rate, manufacturable process for ferroelectric materials, and therefore has potential applications in thin film actuators employing such materials. We would be happy to work with you to try to reproduce compositions optimized for actuator applications with the JVD process, using data obtained by JPL from your patented multi-magnetron sputtering technique. This composition optimization /reproduction will be part of a collaborative Phase I effort. In Phase II we will be willing to collaborate with JPL on fabricating prototype single elements and demonstrating useful large deflections with the composite structures.

Corporate cost sharing by JPC is a possibility that will depend among other things upon the evaluation of the business opportunity at a later stage of the project. Given the current lack of high rate thin film processes for ferroelectrics. we view the area of flexible actuators as one with potential for commercialization of our proprietary JVD technology.

Sincerely,

Takashi Tamagawa
Member of Research Staff

24 Science Park, New Haven, CT 06511 Tel: 203.777-6000 . Fax: 203-777-6007

ICAT

International Center
for Actuators and
Transducers (ICAT)

Kenji Uchino, Director
The Pennsylvania State University
134 Materials Research Laboratory
University Park, PA 168024809

(614) 863.S035
(814) 865-322S
FAX: (814) 865-2326

August 27,1996

Ms. Sarita Thakoor
Jet propulsion Laboratory
MS 303-308
4800 Oak Grove Drive
Pasadena, CA 91109

Sub: DARPA PROPOSAL on "Flexible Microactuators"

Dear Ms. Thakoor,

With reference to our discussion at the ISAF on your concept of flexible micro actuators, I will be delighted to participate as a collaborator on your proposal to DANA on this subject.

In particular, Penn State will participate on the subtask for investigation and optimization of the photoactuation effect in piezoceramic wafers. I, Kenji Uchino, a discoverer of the photostrictive effect in PLZT (lead lanthanum zirconate titanate), and Director of International Center for Actuators and Transducers, Materials Research Laboratory at The Pennsylvania State University, will provide the following spectrum of bimorph samples for this investigation:

- varying thickness of the ceramic wafer
- composition veriation and selected dopants to tune wavelength response and enhance the effect
- variation of orientation of polarization axis
- variation of surface roughness of samples

The cost extimate for this activity at the International Center for Actuators and Transducers at Penn State will be $64K for a duration of one year.

Thank you for inviting Penn State to participate as a collaborator in this project. We look forward to the opportunity to investigate photoactuation for development of optically activated flexible microactuators through this proposed effort.

Yours sincerely,

Kenji Uchino

Kenji Uchino
Professor and Director, ICAT

PENNSTATE

Kenji Uchino
professor of Electrical Engineering
InterCollege Materials Research Laboratory
The Pennsylvania State University
University Park, PA 16802

Educational Background

Ph.D., Physical Electronics, Tokyo Institute of Technology, Tokyo, Japan, 1981
M.S., Physical Electronics, Tokyo Institute of Technology, Tokyo, Japan, 1975
B.S., Physics, Tokyo Institute of Technology, 1973

Professional Experience

Director of the International Center for Actuators and Transducers, The Pennsylvania State University, 1992-
Professor of Electrical Engineering, The Pennsylvania State University, 1991-
Vie President, NF Electronic Instruments, State college, PA, 1992-94
Associate Professor, Faculty of Science and Technology, Sophia University, Tokyo, Japan, 1985-93
Professional Committee Member of Space Shuttle Utilizing Committee in NASDA, Japan, 1986-88
Research Associate, Materials Research, The Pennsylvania State University, 1978-80
Research Associate, Tokyo Institute of Technology, Tokyo, Japan, 1976-85

Professional Associations

Japanese Technology Transfer Association, MITI (Chairman, Society of Smart Actuators/Sensors); American Ceramic Society; IEEE; Materials Research Society; New York Academy of Sciences; Ceramic Society of Japan; Japanese Society of Applied Physics: Executive Associate Editor of Advanced Performance Materials (Kluwer Academic); Editorial Board Member of Ferroelectrics (Gordon and Breach), Sensors and Materials (Myu), Smart Materials and Structures (IOP); J. Intelligent Materials Systems and Structures (VPI), J. Electroceramics (Khmer Academic)

Research Interests

Solid state physics, **especially in ferroelectrics and piezoelectrics, including** basic research on materials, device designing and fabrication process, as well as applicational development of solid state actuators/sensors to precision positioned, ultrasonic motors, smart structures, etc.

Honors and Awards

Outstanding Research Award, Penn Stare Engineering, Society (1996); Highlight Topic Lecture. International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers (1994); Honorary Member, KERAMOS (National Professional Ceramic Engineering Fraternity) (1993); Academic Scholarship, Casio Scientific Foundation (1990); Academic Scholarship, Nissan Motors Scientific Foundation (1990); Best Movie Memorial Award Japan Scientific Movie Festival (1989); Best Paper Award, Japanese Society of Oil/Air Pressure Control (1987)

Selected Publications (from a total of 244; 11 patents: 24 pending)

K. Uchino, Piezoelectric/Electrostrictive Actuators, Morikita Publ. Co., Japan (1986),
K. Uchino, Piezoelectric Actuators (Problem Solving), Morikita Publ. Co., Japan (1991).
K. Uchino, "Electrostrictive Actuators: Materials and Applications," Ceramic Bull. 65(4):647-652 (1986).
K. Uchino, "Ultrasonic Motors," J. Precision Eng. 55(3):51-56 (1989).
K. Uchino, "Micro Mechanism Using Piezoelectric Devices" J. Jpn. Robot Soc. 8(4):119-121 (1990).
K. Uchino, "Ceramic Actuators: Principles and Applications," Mater. Res. Soc. Bull. 18(4):42-48 (1993).
K Uchino, Ferroelectric Ceramics, Mat. Sci. & Tech., Vol. 11, Chapter 12, VCH Publ., FRG (1994).
K. Uchino, "Electro-optic Ceramics and Their Display Applications Ceramics International 21:309-315 (1995).
K. Uchino, "New Applications of Photostriction," Innovations in Materials Research 1:11-22 (1996).
K. Uchino, Piezoelectric Actuators/Ultrasonic Motors, Kluwer Academic Publ., US (1996)

 6/23/96

PENNSTATE

Intercollege Materials Research Laboratory

PHONE (814) 863-834.9
FAX (814) S65-2326
EMAIL stml @alpha mrl.psu.edu

Susan Trolier-McKinstry
Materials Science and Engineering I
149 Materials Research Laboratory
The Pennsylvania State University
University Park, PA 16802

August 28, 1996

Sarita Thakoor,

I am enthusiastic about contributing to the DARPA proposal being submitted by the let Propulsion Laboratory on flexible microactuators. Since, piezoelectric materials provide a combination of high force and simple drive/control circuitry, they arc quite attractive for miniature transducers. In addition to the mobile "insects" being proposed here, the technology developed in this program would also be attractive for a wide variety of micropump and micropositioning applications.

At Penn State there is a long history of work on ferroelectric actuators in both bulk and thin film form. In particular, the ferroelectrics group at the Pennsylvania State University Materials Research Laboratory has extensive experience in the preparation, characterization, and modeling of normal and relaxer ferroelectric materials, My specialty is in the deposition and characterization of thin film ferroics for electromechanical applications. As an example of this, I arn now working with the Army Research Laboratory at Fort Monmouth, New Jersey to establish them as an infrastructure site for lead zircon ate titanate (PZT) films for MEMS. My group is currently studying domain wall motion, stress effects, reliability, and aging issues in PZT film-based actuators. We also recently demonstrated a 0.25% strain in oriented $PbZrO_3$ phase switching films.

The Penn State contribution to the program in the first year includes assessment of the possibility of using micromachining techniques in silicon to prepare piezoelectrically-actuated thin films for miniature transducers which could easily be embedded in a flexible structure. In subsequent years, work on preparing devices and maximizing the electro-mechanical actuation will be performed. It is estimated that $20,000 would be used in the first year, with $80,000/year for Phases 2 and 3.

Sincerely,

Susan Trolier-McKinstry

Susan Trolier-McKinstry

Susan Trolier-McKinstry
Assistant Professor of Ceramic Science and Engineering
Intercollege Materials Research Laboratory
The Pennsylvania State University
University Park, PA 16802

Educational Background

Ph.D., Ceramic Science, The Pennsylvania State University, 1992
M.S., Ceramic Science, The Pennsylvania State University, 1987
B. S., Ceramic Science and Engineering, The Pennsylvania State University. 1987 (honors)

Professional Experience

Assistant Professor, Ceramic Science and Engineering. The Pennsylvania State University, 1992-
Visiting Scientist, Ecole Polytechnique Federale de Lausanne, *Summer* 1996.
Summer Research Faculty Fellow, Electronic and Power Sources Directorate, U.S. Army Research Labs., Summer 1993
Instructor, Corning Inc. Materials Science Course on "Oxide Engineering," 1990- .
Visiting Research Trainee, Hitachi Central Research Laboratory, Hitachi Ltd., Kokubunji, Japan, March-August 1988

Professional Associations

American Ceramic Society; Materials Research Society: IEEE; Keramos (Vice President, Treasurer), American **Society** for Engineering Education, ASM

Research Interests

Electroceramics. ferroelectrics, structure-microstrucwrc property relations in thin films, spectroscopic ellipsometry

Honors and Awards

NSF CAREER Award; Graduate Student Awards from MRS and the American Ceramic Society; Xerox Award for Research in Materials Science by a Master's Degree Student; George Brindley Prize for Undergraduate Excellence in Crystal Chemistry

Selected Publications

P. Aungkavattana, B. Haartz, C. O. Ruud, and S. Trolier-McKinstry "In-Situ X-ray Studies of Phase Transformations in Lead Zirconate Titanate Thin Films During Annealing." Thin Solid Films 268102-107, (1995),

K. Yamakawa, S. Trolier-McKinstry, J. P. Dougherty, and S. B. Krupanidhi, "Reactive Magnetron Co-Sputtered Antiferroelectric Lead Zirconate Titanate Thin Films," Appl. Phys. Lett. 67(14) 2014.2016 (1995).

S. Trolier-McKinstry, J. Chen, K. Vedam, and R. E. Newnham, "In-Situ Annealing Studies of Sol-Gel Ferroelectric Thin Films by Spectroscopic Ellipsometry," J. Amer. Ceram. Sot. 78[7] 1907-1913 (1995).

G. R. Fox, S. Trolier-McKinstry, L. Casas, and S. B. Krupanidhi, "Pt/Ti/SiO_2/Si Substrates," J. Mat, Res. 10[6] 1508-1515 (1995),

S. Trolier-McKinstry, H. Hu and A. H. Carim, "Spectroscopic Ellipsometry Investigations of Amorphous Silicon Nitride Thin Films," J. Electrochem. Sot, 14 1:2483-2486 (]994),

S. Trolier-McKinstry, H. Hu, S. Krupanidhi, P. Chindaudom, K. Vedam and R. E. Newnham, "Spectroscopic Ellipsometry Studies on Ion Beam Sputtered $Pb(Zr,Ti)O_3$ Films on Sapphire and Pt-Coated Silicon Substrates," Thin Solid Films 230:15-27 (1993).

R. E. Newnham and S. Trolier-McKinstry, "Crystals and Composites," J. Appl. Cryst. 23:447-457 (1990). .

S. E. Trolier, P. A. Fuirier, S. Atkinson, J. H. Adair and R. E. Newnham, "Dissolution of $YBa_2Cu_3O_{(7-x)}$ in Various Solvents,"' Bull, Amer. Ceram. Sot. 67(4):759-762 (198 S).

S. E. Trolier, Q.C. Xu and R.E. Newnham, "A Modified Thickness Extensional Disk Transducer," IEEE Trans. Ultrason., Ferroelectrics Freq. Control 35(6):839-842 (19S8).

8/28/96

UNIVERSITY OF CALIFORNIA, BERKELEY

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DEPARTMENT OF INTEGRATIVE BIOLOGY

BERKELEY, CALIFORNIA 94720

Professor Robert J. Full
Department of Integrative Biology
University of California at Berkeley
Berkeley, CA 94720
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U.C. BERKELEY POLY-PEDAL LAB

August 27, 1996

Dr. Sarita Thakoor
Jet Propulsion Laboratory

"The U.C. Berkeley Comparative Biomechanics Consortium is pleased to assist the Jet Propulsion Laboratory in a project on flexible microactuation. We will provide no cost consulting in Phase 1 during the design and fabrication of the microactuator. We would gladly be consultants throughout the project, In Phase 2, we can provide biological inspiration toward the development of a mechanism for advanced mobility. In particular, my research focuses on the design of limb actuation in arthropods (insects and crustaceans). I am confident that Professor Michael Dickinson will also be invaluable if aerial locomotion is an objective (his research focuses on the control of flight in flies). We have served in this role before (e.g. DARPA funded Rockwell International - Autonomous Legged Underwater Vehicle Project) and provided many design ideas that have come directly from our basic research on animal locomotion.

Thank you.

Sincerely yours,

Robert J. Full

Robert J. Full
Professor

97 Salary Budget Sheet 8127196

Robert Full and Michael Dickinson

Stan date: 9/1/97
End date: 8/31/98

A. SENIOR PERSONNEL	
1. Faculty I (Robert Full) 1 summer mo.	7,456
Faculty II (Michael Dickinson) 1 summer mo.	5,671
B. OTHER PERSONNEL	
1. POST DOCTORAL ASSOCIATE 100% @ 12 mos	31,400
2. OTHER PROFESSIONALS	0
3. GRADUATE STUDENTS	0
4. UNDERGRADUATE STUDENTS	0
5. SECRETARIAL-CLERICAL	
6. OTHER	
TOTAL SALARIES AND WAGES	44,527
C. FRINGE BENEFITS	3,429
TOTAL SALARIES AND BENEFITS	47,956
D. PERMANENT EQUIPMENT	0
E. TRAVEL	
1. DOMESTIC	0
2. FOREIGN	0
F. PARTICIPANT SUPPORT COSTS	
1. STIPENDS	0
2. TRAVEL	0
3. SUBSISTENCE	0
4. OTHER	0
TOTAL PARTICIPANT COSTS	0
G. OTHER DIRECT COSTS	
1. MATERIALS AND SUPPLIES	0
2. PUBLICATIONS	0
3. CONSULTANT SERVICES	0
4. COMPUTER SERVICES	0
5. SUBCONTRACTS	0
6. OTHER	0
TOTAL OTHER DIRECT COSTS	0
H. TOTAL DIRECT COSTS	47,956
I. TOTAL INDIRECT COSTS 49.90%	23,930
J. DIRECT AND INDIRECT COSTS	71,886

Benefits: faculty 8.9%; Postdoc. 7.2%

Print Date: 8/27/96

- 28 -

CURRICULUM VITAE

Robert Joseph Full

Education
Ph.D. State University of New York at Buffalo 1984 M.A. State University of New York at Buffalo 1982 B.A. State University of New York at Buffalo 1979

Professional Positions
Professor University of California, Berkeley 1995-present
Associate Professor University of California, Berkeley 1991-1995
Assistant Professor University of California, Berkeley 1986-1991
Post doctoral Lectureship The University of Chicago, 1984-1986 N.S.F. Research Assistant S. U.N.Y. Buffalo, Summers 1979-1984 Teaching Assistant S. U.N.Y. Buffalo, 1979-1984

Honors and/or Awards
Summa Cum Laude , S. U.N.Y. Buffalo
Phi Beta Kappa , S. U.N.Y. Buffalo
Presidential Young Investigator Award, NSF
Invited Scholar - Oklahoma Scholars Leadership Enhancement Program
Frontiers of Science speaker - National Academy of Sciences invited speaker - National Academy of Sciences Annual Meeting 1995 G.W. Thorn Award - Distinguished Alumni, S. U.N.Y. Buffalo
Friday Evening Lecturer - MBL, Woods Hole

Selected Research Publications
1. Full, R.J. and Blickhan, R. and Ting, L.H. 1991. Leg design in hexapedal runners. J. exp Bio. 158, 369-390.

2. Full, R.J. 1993. Integration of individual leg dynamics with whole body movement in arthropod locomotion. In: Biological Neural Networks in Invertebrate Neuroethtology and Robots. (eds. R. Beer, R. Ritzmann and T McKenna). Academic Press. Boston. pp. 3-20.

3. Full, R.J. and Koehl, M.A.R. 1993. Drag and lift in running insects. J. exp Bio. 176, 89-103.

4. Ting, L. H., Blickhan, R. and Full, R.J. 1994. Dynamic and static stability in hexapedal runners. J. exp Bio. 197, 251-269.

VARITY Kelsey-Hayes

Research and Development Cen
2500 Green Road
Ann Arbor, Michigan 48105

Telephone 313 769 5690
Fax 3139961301

8/27/96

Sarita Thakoor
Member Technical Staff
Jet Propulsion Lab
MS 303-308
4800 Oak Grove Drive
Pasaden%CA91109

Dear Dr. Thakoor:

With reference to our discussion at the ISAF on your concept of flexible microactuators. 1 will be delighted to participate as a collaborator on your proposal to DARPA on this subject.

In particular, Varity Kelsey-Hayes will be interested to provide Vehicle Stability Management and Collision Avoidance support infrastructure for the demonstrations of the micro electro/opto-mechanical system element in Phase 2 and the proof of concept system demonstrate ion in Phase 3.

Varity Kelsey-Hayes has been supplying high quality automotive components to the automotive market since the early part of this century. It pioneered and developed the first ABS(anti-lock broke system) for automotive applications in 1968. Today, the company is one of the largest entities in the world in researching, developing and manufacturing ABS. In 1992, its annual sales exceeded $2.42 billion,

Vehicle Stability Management is in fact an extension of the ABS system and traction control concepts. The purpose of vehicle Stability Management is to improve a vehicle safety in dynamic handing situations. We can see potential applications like microactuator for valve controller in the vehicle, and also opto-mechanical system in collision avoidance. I have been working on piezoelectric actuators for five years. I think piezoelectric actuators have a lot of potential to be microactuators in terms of amount of force generated, m i nature size and response speed.

Thank you for inviting Varity Kelsey-Hayes to participate as a collaborator in this project. We look forward to the opportunity to develop flexible microactuators based advanced micromobility systems through this proposed effort.

Sincerely,

Joe Ye
Senior Product Engineer

Joe Ye
Varity Kelsey-Hayes
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Ann Arbor, MI 48105
Tel:313-769-2760 Fax:313 996 1301

Work Experience:

Variety Kelsey-Hayes
March 1996- Present
Senior Product Engineer Research arid Development in the area of Vehicle Stability Management.

Delphi - E **Division of GMC**
July, 1994 -Feb, 1996
Product Engineer. Design& Develop various types automotive **sensors, such as knock sensors, pressure sensors, crank speed sensors, and rough road sensors.**

International Center for Actuator & Transducer **Penn State Univ.**
Aug, 1992- July, 1 *994*
Research assistant. Design new type ultrasonic motor and using simulation for the Office of Naval Research Project.

Electrical Engineering Department **Penn State Univ.**
Sept, 1992- Jan, **1993**
Research Assistant. Neural network and Fiber-optics Communication.

Zybron Company **Dayton, Ohio**
July, 1992- Sept, 1 992
Develop new Magneto-Optic recording disk for Air Force Project. Familiar with Multi-Magnetron, Ion Beam and Laser Ablation sputtering method.

Corning - China Television Glass Program **China**
July, 1989- Aug., 1990
Process Engineer and Technical Liaison.

Education:

The Pennsylvania State University **University Park**
Ph.D. candidate, major in Electrical Engineering
M-S., major in Electrical Engineering **May, 1994**

University of Science & Technology of China **China**
B.S. major in Materials. July, **1989**
Massachusetts Institute of Technology. **July, 1996**
Completed a Summer Program in Microsystems

Awards:

Recipient of **DARPA** (Defense **Advanced Research Project Agency)** for research project " Smart materials as sensor & actuator" 1992

"Who is Who in Science & Technology" **1995**

Presentations:

"Ring-type Ultrasonic Motor"	IEEE, **1994**
"**New Power Generated** Ultrasonic Motor"	***ONR*** **workshop** 1994
"**Ultrasonic** Motor and Its **Simulation**"	**Acers, 1994**
"**Using PLZT** as Spatial Light Modulator"	**Acers,** 1994
'Using **photo sensitive material as actuator"**	**Acers, 1993**

Acers(American Ceramic Society), ONR (Office of Naval Research)

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EDUCATION:

M. Phil. (Physics) University of Delhi, India, 1979

“[dissertation Title: On the calculation of tunneling transmission coefficient for metal-insulator-metal junction.”

M. SC. (Physics) University of Delhi, India, 1977
B. SC. (Physics Honors) University of Delhi, India, 1975

CAREER HISTORY:

June 1985- Present
Member Technical Staff, Jet Propulsion Laboratory, CALTECH

June 1984 - May 1985
Physicist, Jet Propulsion Laboratory, CALTECH

Aug 1980 - Jan 1982
Senior Research Fellow, Center of Energy Studies, Indian Institute of Technology, New Delhi 110016, INDIA

Aug 1978 - July 1980
Research Fellow, Center of Energy Studies and Department of Physics, Indian Institute of Technology, New Delhi 110016, INDIA

Aug 1977 - July 1978
Research Fellow, Council of Scientific and Industrial Research, Department of Physics and Astrophysics, University of Delhi, INDIA

CURRENT RESEARCH INTERESTS include microactuation/MEMS and its applications to robotics and active control. Particularly, ferroelectric/piezoceramics for robotics, micromobility, biologically inspired advanced mobility, microactuators for shape control and biomedical applications, sensors, and non-volatile memories.

RESEARCH EXPERIENCE:

Thin **Film Techniques:** Vacuum and e-beam evaporation, reactive magnetron sputtering, CVD, electrodeposition, photolithography, reactive ion etching

Characterization: Advanced structural, electrical, surface-interface and optical methods of analysis

Materials: Perovskite Titanates particularly ferroelectrics, **amorphous silicon, tungsten oxide, superconductors, II-VI compounds**

Electro-Chemistry: Coupled chemical electrochemical reactions, chronopotentiometric and coulometric techniques

Device Engineering/Innovative Concepts: Flexible microactuators, High displacement slit actuator: 1. RAINBOW (Reduced and internally Biased Oxide Wafer) and 2. Double amplification bimorph-flextensional combination, Piezoceramic bimorph as an optically driven cantilever leg, Optical Actuation for Shape Control, High speed photoeffects, Applications of High Speed Photoeffects for electro-optic computation, High Speed- High resolution Diagnostic Technique for Ferroelectric Thin Films, Optically propelled self sustained vibrations, Miniature motor, Tetherless Optically controlled Microrobot, Embedded temperature sensor, High capacitance density thin films for integrated circuit Systems, Novel thin film devices for electronic neural networks, non-volatile ferroelectric thin film memory devices, Superconducting NbN junctions for quantum mixers, $CdS\backslash Cu_xS$ thin film solar cells

Marketing Initiative: Demonstrated initiative and competence in breaking into the new area of ferroelectrics and successfully obtaining continued funding for the past seven years at JPL. Current goal is to launch Microactuation/MEMS initiative at JPL and develop Miniature Inexpensive, solar driven autonomous advanced mobility for Mars exploration utilizing innovative biomorphic control.

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2. S. Thakoor, J. L. Lamb, A. P. Thakoor, and S. K. Khanna, "High T_C Superconducting NbN films deposited at Room Temperature", *Journal of Applied Physics*, 58,4643 (1985).

3. S. Thakoor, D. M. Strayer, G. J. Dick and J. E. Mercereau, "A Lead-on-Sapphire Superconducting Cavity of Superior Quality", *Journal of Applied Physics, 59, 854* (1{186).

4. S. Thakoor, H. G. LeDuc, A. P. Thakoor, J. Lambe, and S. K. Khanna, "Room Temperature Deposition of NbN for Superconducting-Insulator-Super-conductor Junctions", *J. Vat. Sci. & Tech. A.,* May-June A, 4 (3), 528(1986).

5. S. Thakoor, H. G. LeDuc, J. A. Stern, A. P. Thakoor, and S. K. Khanna, "Insulator Interface Effects in Sputter-Deposited NbN/MgO/NbN (superconductor-insulator-superconductor) Tunnel Junctions", *J. Vat. Sci. Tech. A,* July/August 5 (4) Pt. III, 1721 (1987).

6. H. G. LeDuc, J. A. Stern, S. Thakoor, and S. K. Khanna, "All Refractory NbN/MgO/NbN Tunnel Junctions", ***IEEE Transaction on** Magnetics*, ***MAG-23 (2)*** 863 (1987).

7. S. Thakoor, A. Moopenn, T. Daud and A. P. Thakoor, "Solid State Thin Film Memistor for Electronic Neural Networks", *Journal of Applied Physics, 67 (6), 3132 (1990).*

8. R. Rarnesham, S. Thakoor, T. Daud, and A. P. Thakoor, "Solid-State Reprogrammable Analog Resistive Devices for Electronic Neural Networks", *J. Electrochem. Sot., 137 (6), 1935(1990).*

9. S. Thakoor, "Non-destructive Readout (NDRO) from Ferroelectric PZT thin FilmCapacitors", Ceramic Transactions: Ferroelectric Films, Edited by A. S. Bhalla and K. M. Nair (Published by American Ceramic Society, Westerville, Ohio), 25, 251 (1991)

10, S. Thakoor, "High Speed, Non-destructive Readout from Thin Film Ferroelectric Memory", Appl. Phy. Lett. 60, 3319, 1992.

11. S. Thakoor, "High Speed, Optoelectronic Non-destructive Readout from Ferroelectric Thin Film capacitors", Ferroelectrics, **134**, 355, 1992.

12. S. Thakoor, and J. Maserjian, "Photoresponse Probe of the space charge distribution in Ferroelectric PZT thin film **memory** capacitors" J. Vat. Sci. &Tech A, **12**, 295, Mar/April(1 994).

13. S. Thakoor, "High Speed, Optoelectronic Response from the Edges of lead Zirconate Titanate Thin Film Capacitors", Appt. Phy. Lett. 63(23), 3233, 1993.

14. S. Thakoor, "Enhanced Fatigue and Retention in Ferroelectric Thin film Memory Capacitors by Post-top-elecrtrode Anneal treatment", Journal of Appl. Physics, 75 (1 O), 5409, May 15 (1994).

15. S. Thakoor, J. Maserjian, J. Perry, "An Optical Probe for Ferroelectric Thin Film Memory Capacitors", Integrated Ferroelectrics 4, 333 (1994).

16. S. Thakoor, E. Olson, and R. H. Nixon, "Optically Addressable Ferroelectric Memory and its Applications" Integrated Ferroelectrics", 4, 257 (1994).

17. S. Thakoor and A. P. Thakoor, "Optically Addressed Ferroelectric Memory with Non-Destructive Readout", Applied optics 34, 3136 (1995).

18. S. Thakoor, A.P. Thakoor, and L. E. Cross, "Optical Non-Invasive Evaluation of ferroelectric Films/Memory Capacitors" Materials for Smart Systems", Vol. 360, P 157(1995).